DOI: https://doi.org/10.3986/ac.v53i2-3.13850

TOPOGRAPHIC CONDITIONS FOR SPATIAL DISTRIBUTION OF DOLINES IN VALJEVO–MIONICA KARST, WESTERN SERBIA

TOPOGRAFSKE RAZMERE ZA PROSTORSKO RAZPOREDITEV KRAŠKIH VRTAČ V MESTIH VALJEVO IN MIONICA, ZAHODNA SRBIJA

Marko V. MILOŠEVIĆ[1*], Jelena ĆALIĆ[1] & Milovan MILIVOJEVIĆ[1]

Abstract UDC 52-323.7:551.435.82(497.11)

Marko V. Milošević, Jelena Ćalić & Milovan Milivojević: Topographic conditions for spatial distribution of dolines in Valjevo–Mionica karst, western Serbia

Valjevo–Mionica karst is a limestone area within the easternmost flanks of the Internal Dinarides in western Serbia. In the spatial extent of 380 km2, it hosts typical karst landforms, primarily dolines, blind valleys, dry valleys and caves. Dolines are present on 75% of the total area, and the exact number of them within the area outline is 5319. The aim of the study is to determine the guidance factors for the spatial distribution of dolines, primarily morphological, while lithological, tectonic and climatic factors are presented at the basic level. Morphological factors in this study are analysed through morphometrical characteristics and calculations, which include the elevation, the mean topographical slope and the landform classification based on geomorphons. Digital elevation models with resolutions 90 m and 30 m are used. Data sources for doline positions were the topographical maps of 1:25,000 scale.

Spatial distribution of dolines in the study area is rather uneven. Three zones (clusters) of higher concentration may be distinguished, where 34% of the total study area hosts 72% of dolines. These three zones are the karsts of the villages Lelić, Bačevci and Robaje, divided by deep canyon valleys. Maximum density of dolines, judging by the Kernel density method, is 33 dolines per km^2 in the zone of the Stapar village, at the northwestern outskirt of the study area. The main factors influencing the spatial distribution of dolines are the topographical slope and the phases of morphological/hydrographical evolution of the area.

Keywords: karst doline, Point Pattern Analysis, doline density, geomorphons, western Serbia.

Izvleček UDK 52-323.7:551.435.82(497.11)

Marko V. Milošević, Jelena Ćalić & Milovan Milivojević: Topografske razmere za prostorsko razporeditev kraških vrtač v mestih Valjevo in Mionica, zahodna Srbija

Kras v mestih Valjevo in Mionica je apnenčasto območje na skrajnem vzhodnem pobočju Notranjih Dinaridov v zahodni Srbiji. Na površini 380 km^2 so značilne kraške oblike, predvsem vrtače, slepe doline, suhe doline in jame. Vrtače se pojavljajo na 75 % celotnega območja, na tem območju jih je natančno 5.319. Cilj študije je določiti usmerjevalne dejavnike za prostorsko razporeditev vrtač, predvsem morfološko, na osnovni ravni pa so predstavljeni litološki, tektonski in podnebni dejavniki. Morfološki dejavniki so v tej študiji analizirani z morfometričnimi značilnostmi in izračuni, ki vključujejo nadmorsko višino, povprečje topografskega naklona in razvrstitev reliefnih oblik na podlagi geomorfološke dejavnosti. Uporabljeni so digitalni modeli višin z ločljivostjo 90 m in 30 m. Vir podatkov za položaj vrtač so bili topografski zemljevidi v merilu 1 : 25.000.

Prostorska razporeditev vrtač na proučevanem območju je precej neenakomerna. Razlikujemo lahko tri območja (grozde) z večjo koncentracijo vrtač, kjer je na 34 % celotnega proučevanega območja 72 % vrtač. Ta tri območja so kraška območja vasi Lelić, Bačevci in Robaje, ločujejo pa jih globoke kanjonske doline. Največja gostota vrtač po metodi Kernel Density Estimator je 33 vrtač na km^2 na območju vasi Stapar na severozahodnem obrobju proučevanega območja. Glavni dejavniki, ki vplivajo na prostorsko razporeditev vrtač, so topografski naklon in faze morfološkega/hidrografskega razvoja območja.

Ključne besede: kraška vrtača, analiza točkovnih vzorcev, gostota vrtač, geomorfološke dejavnosti, zahodna Srbija.

[1] Serbian Academy of Sciences and Arts, Geographical Institute Jovan Cvijić, Đure Jakšića 9/3, Belgrade, Serbia, email: m.milosevic@gi.sanu.ac.rs

[*] Corresponding author

Prejeto/Received: 16. 7. 2024

1. INTRODUCTION

Throughout the history of karstology as a scientific discipline, the most studied karst surface landforms have been the dolines. Their first thorough overview and classification was given by Jovan Cvijić (1893) in his thesis „Das Karstphänomen" (Ford, 2007). Although his classification is morphographical in the introductory part, the subsequent pages provide the explanation of the solution process within the dolines, as well as their types: (1) „normal" dolines (presently used equivalent term is „solution dolines"); (2) abysses (steep-sided dolines that continue downwards into caves); and (3) alluvial dolines. The term abyss is not present in contemporary classifications, but it is worth mentioning in the context of the early awareness of the role of vertical shafts in connecting the surface and underground karst. The shortfall of Cvijić's classification was the exclusion of the collapse as a doline morphogenetic process.

A significant upgrade of systematical overviews of dolines was given by Cramer (1941), who reviewed virtually all available references of the time, including the terminology of karst surface forms in a number of native languages on three continents. His typology consists of five types of dolines: collapse, solution, suffosion, alluvial and „schwund" dolines (a sub-type of suffosion dolines).

During the upcoming decades, in the second half of the 20th century, the doline studies have been upgrading both in the approach and the methodology of research. The number of classifications was increasing. Jennings (1985) kept three Cramer's types (collapse, solution and alluvial), but included subsidence and subjacent dolines. Ford and Williams (1989, 2007) offered four types in 1989 book (solution, collapse, subsidence, suffosion), but increased the number of doline types in 2007 edition to six, adding dropout, buried and caprock dolines, excluding the term subsidence dolines. Solution dolines genesis was diversified to two types of initiation, introducing the point recharge dolines and drawdown dolines (Ford & Williams, 2007). Systematic overview of doline morphogenetic processes was given by Gams (2000), while certain aspects of evolution and classifications were additionally elaborated by Sauro (2003). Engineering classification, rather similar to the aforementioned ones, was published by Waltham and Fookes (2005). The most recent state-of-the-art general review of karst dolines is given by De Waele and Gutierrez (2022). Precise field measurements with mathematical and statistical processing of small dolines morphology was carried out by Šušteršič (2006), comparing them approximately with a "paraboloid that hardly differs from a cone". Pardo-igúzquiza et al. (2016) studied the population of 3100 dolines of Sierra Gorda karst massif in southern Spain, highlighting the main areas of doline density, and determining that the doline size follows a fractal law. LiDAR-based studies of dolines have been presented by Telbisz et al. (2016, 2021, 2024) The first analyses of spatial distribution of karst depressions were given by Williams (1972) for New Guinea, and especially by Kemmerly (1982), in his study of karst surface in south-eastern USA. Apart from depression density (no./km^2), doline swallet order, and interdoline spacing, the author presented a multigenerational diffusion and competition process model, showing subpopulations, clustered sets containing second-order swallet dolines revealing geomorphic competition for catchment area, as well as a positive correlation between interdoline rim spacings of the small swallet order and the sum of their respective major axial lengths. Verbovšek and Gabor (2019) presented excellent morphometric analysis of spatial distribution of dolines, as well as delineation principles, pitting index, depth, circularity index, volume, area, and orientation.

Regarding the study area of Valjevo karst in western Serbia, the first historical description of dolines was given by Pavlović (1889) who spotted them in the southeastern foothill of Vlašić Mt. In the subsequent paper on this matter (Pavlović, 1907), pedological and hydrographical characteristics of dolines were described. Cvijić (1912) noted that the dolines are the most numerous landforms in the area of the Lelić village, presently known in literature by the name Lelić karst. The author noted the linear distribution of dolines within the dry valleys, explaining it as a consequence of lowering the groundwater level. Petrović (1951) observed the morphological differences among the dolines in the neighbouring karst area of Bačevci village (Bačevci karst) and the dependence of their distribution on particular host landforms. Similar views on the dolines in the area were given by Jovanović (1956), Lazarević (1996) and Dragićević (2007).

The aims of this study are: (a) to define the outlines of Valjevo–Mionica karst; (b) to test multiple terrain analysis methodological procedures in function of dolines study, (c) to determine the total number, morphological patterns and density of dolines, (d) to determine the dependence between the spatial distribution of dolines and the morphometric and morphological characteristics of the area, and (e) to test the dependence of doline distribution on morphostructural pattern.

2. STUDY AREA

2.1. OUTLINE OF THE VALJEVO–MIONICA KARST

Valjevo–Mionica Karst is a karstic terrain in western Serbia, at the eastermost outskirts of the Internal Dinarides. The spatial extent, as well as the name of the area, has varied during the exploration history. In the works of Cvijić (1912), Petrović (1951) and Dinić (1959) the karstic area is considerably smaller, consisting of two components – Bačevci karst and Lelić karst. Jovanović (1956) offered extremely large extension of the karst area, which includes the mountains Medvednik, Jablanik, Povlen, Maljen, as well as Vlašić (NW of Valjevo, not visible on Figure 1 below), naming it Valjevo Karst. This name and the detailed outline of the area has been used by Lazarević (1996) as well, encompassing karst in the watersheds of Jablanica, Gradac and Ribnica rivers, but excluding Vlašić Mt.

In order to perform GIS analyses of any studied area, a precisely determined outline is needed, based on a set of relevant criteria. In this case, the selected data included lithological, morphological and hydrographical characteristics, as well as the administrative territorial units. Limestone terrains with pronounced karstic landscapes are present in northwestern, western, central, southern and eastern parts of the Valjevo municipality, extending further to the east to the western and central parts of Mionica municipality (Figure 1). Apart from the main karst area (A), which includes about 93% of the territory, there are additional five karst fragments („exclaves“) (Table 1). The largest part of the Valjevo–Mionica karst lies within the Kolubara River watershed (including the rivers Obnica, Jablanica, Gradac, Lepenica and Ribnica), while the peripheral units in the western part belong to the watersheds of the Jadar River and the Trešnjica River.

Table 1: Spatial units, percentages of karst, and the respective number of dolines.

Unit	km^2	Karst areas (%)	number of dolines	Share in total area %
A	352,73	92,75	5218	98,00
B	1,07	0,30	29	0,50
C	1,73	0,45	9	0,2
D	15,38	4,05	63	1,3
E	3,56	0,93	0	0
F	5,80	1,52	0	0
Σ	380,27	100	5319	100

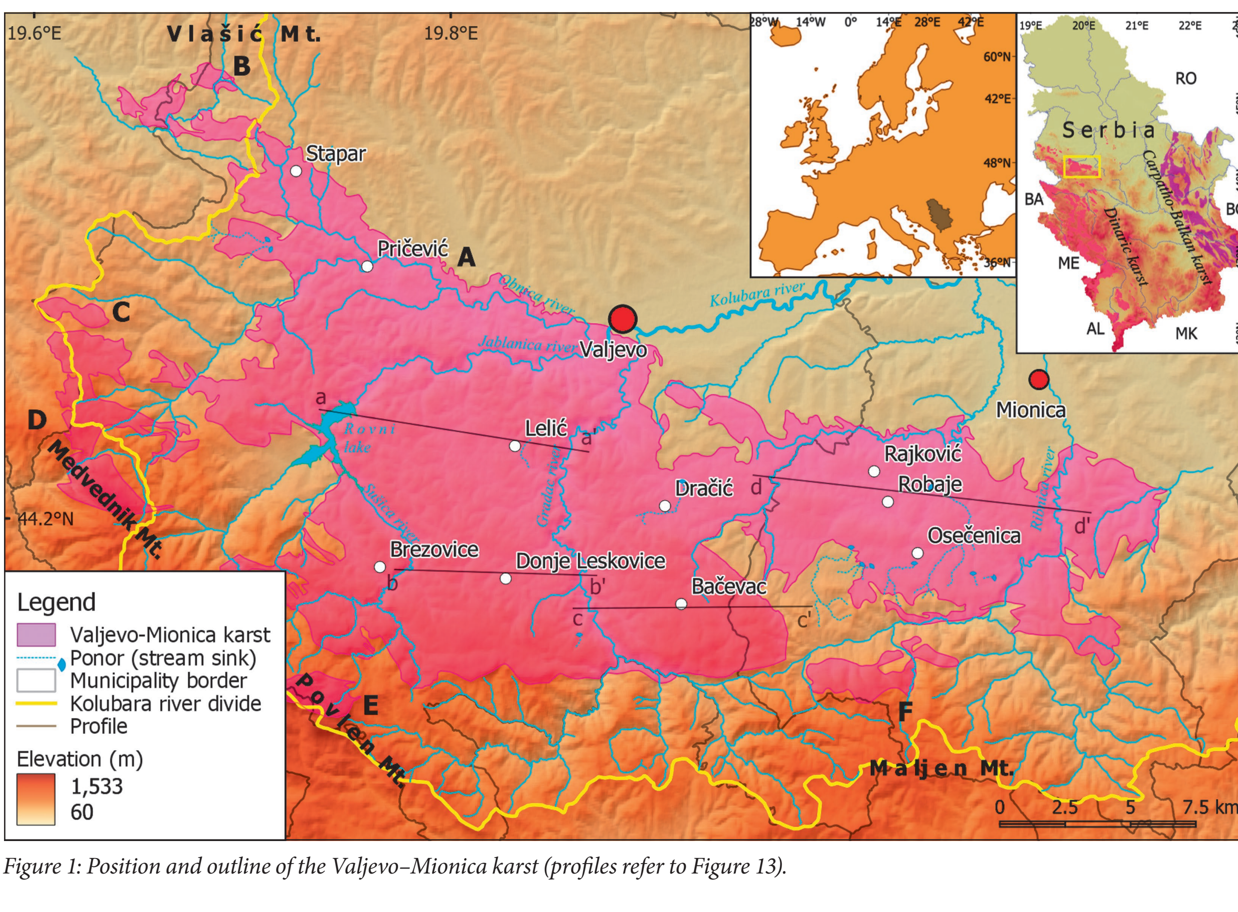

Figure 1: Position and outline of the Valjevo–Mionica karst (profiles refer to Figure 13).

2.2. PHYSICAL-GEOGRAPHICAL CONDITIONS

As a north-easternmost part of the Dinaric orogen, the present Valjevo-Mionica area dates back to the late Mesozoic and early Cenozoic, the time of the closure of a part of the Neotethys called the Vardar Ocean (Cvetković et al., 2019). During the Mesozoic, the ocean hosted the deposition of the Triassic, Jurassic and Cretaceous limestones which afterwards gradually uplifted to the present positions. Compression of carbonates has been caused by the collision of the African and European plates (Stampfli & Borel, 2002). Within the karst area, pure Triassic limestones are present on 55% of the territory, while the remaining part is composed of Jurassic and Cretaceous limestones with marls, shales, sandstones and dolomites. About 4.5% of the area is built of non-carbonate rocks enclaves consisting of alluvial sediments, porphyry and pyroclastics (Mojsilović et al., 1975).

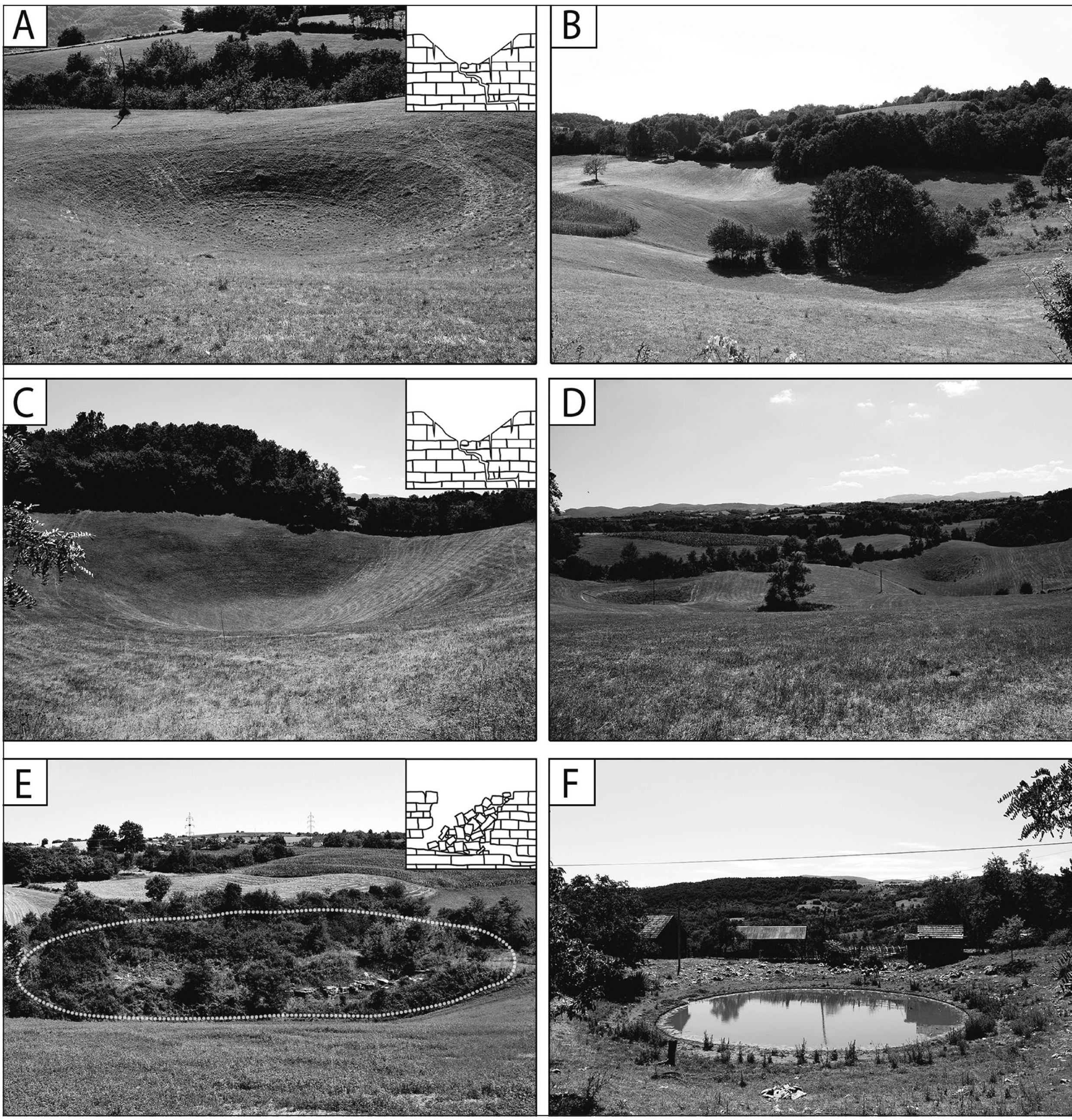

Figure 2: A – Solution doline in Bačevac; B – Lined-up dolines in a blind valley in Dračić; C – Solution doline in Lelić; D – Lined-up dolines in a blind valley in Lelić; E – Collapse doline in Osečenica; F – Cultivated doline in Robaje, (inset sketches in A, C, E redrawn after Waltham and Fookes, 2005).

Valjevo-Mionica karst lies in the elevation belt from 160 m to 1301 m. Morphogenetic types of landforms include fluvial, karst and mass movement forms. Fluvial landforms are river valleys, river terraces and alluvial plains, while the gorges of the Sušica, Gradac and Ribnica rivers are fluviokarstic forms. Karstic landforms are dolines, dry valleys, blind valleys and caves (Petnička, Degurićka, Šalitrena, Ribnička, Lenčina, Dragov Ponor, etc).

According to the Köppen climate classification, the studied area belongs to the Cfb type – warm and humid, with warm summers (Milovanović et al., 2017). The mean annual air temperature is 9°C to 11°C, while the average yearly precipitation is 800-1000 mm, depending on the elevation (Milovanović et al., 2018). The pluviometric regime is of continental type – the maximum precipitation occurs in late spring and early summer (May, June), while the minimum is during the winter (February). All permanent rivers flowing through the Valjevo-Mionica karst are of allogenic character (Obnica, Jablanica, Gradac, Lepenica and Ribnica). Among the sinking rivers, the longest are Jazina (6.2 km), Plandište (5.3 km), Bukovik (2.8 km) and Osečenički Potok (2.7 km). Forests cover 52% of the Valjevo-Mionica karst, mostly deciduous (96.5%) and, in small percentage, coniferous forests (3,5%)

3. DATA SOURCES AND METHODS

The primary data sources for doline locations have been the 1:25,000 scale topographical maps, published by the Military-Geographical Institute from Belgrade. Using this scale, all technically "visible" dolines deeper than 2.5 m were mapped, meaning that there was no generalization of the doline number, as it is the case with the scales 1:50,000 and 1:100,000 (Borisov, 2014). This implies that the spatial relations of doline distribution on 1:25,000 scale topographical maps are credible, regardless of the fact that they do not show the dolines of less than 2.5 m depth. During the process of digitizing, the dolines are defined as points positioned exactly on the graphical mark for the bottom of the doline (Pahernik, 2012). More precisely, this is the (-) (minus sign) below the lowest closed contour. In cases when the dolines are marked without the contours, but only with a topographical symbol, the lowest point is considered to be positioned in the very center of the symbol.

Data source on the topographical characteristics of the terrain (slope and elevation of the areas with dolines) was the Digital Elevation Model (DEM) of 90 m resolution (SRTM). Morphological analyses of landforms were carried out using the 30 m resolution DEM (SRTM).

Lithological composition data have been obtained in the process of digitizing and vectorization of the Basic geological map 1:100.000 (sheets Valjevo, Gornji Milanovac and Vladimirci) and subsequent classification to three groups: (1) pure limestones (Triassic and Cretaceous limestones; Triassic schisty limestones; Triassic limestone breccias), (2) limestones combined with other lithologies (Permian limestones with shales; Cretaceous marls, sandstones and limestones), and (3) non-carbonate rocks (alluvial sediments, porphyry and pyroclastic rocks).

Within the process of determining the spatial distribution of dolines, the Point Pattern Analysis (PPA) was used (Yuan et al., 2020). The main characteristics of distribution were determined using the descriptive statistics (Gong, 2002; O'Sullivan & Unwin, 2010). The dolines in the area of Valjevo-Mionica karst were subject to the analyses of the central tendency and dispersion (determining the standard deviation and standard deviational ellipse). Variations in the doline density were analysed using the Global and Local density. The global density is a relation between the total number of the dolines within a studied territory and its total area (homogenous density). On the other hand, in order to determine the heterogeneous density, the methods for local density were applied. In this context, the analysis of square (quadrat) density at the level of 1 km^2 was used, as well as the Kernel density in the search radius of 568 m.

Geomorphons are a new method of digital representation and analysis of landforms which does not rely on differential geometry (Stepinski & Jasiewicz, 2011). They are the basic microstructures of landscapes, considered to be simultaneously relief attributes and relief types (Jasiewicz & Stepinski, 2013). This method of autoclassification is based on the concept of a local ternary pattern, the values of which may be 0, +1, or -1. The value is defined in relation to the central (focal) cell. The neighboring cell will have the value of "+1" if its value is larger than the value of the central cell. If the values are equal, it will have the value "0", while for the smaller value than the central cell, the value will be "-1". The neighbouring cells are not necessarily the ones in the direct contact with the central cell, but also those within the line-of-sight along 8 main directions. The values 0, +1, or -1 are defined by flatness threshold (t), which is the minimal value of the right triangle (line-of-sight angle, zenith or nadir) considered to be considerably different from the horizon (Stepinski & Jasiewicz, 2011). Theoretically, the ternary pattern may support 6561 possible variations, but they can be mainly depicted with 10 geomorphons: flat, peak, ridge, shoulder, spur, slope, pit, valley, footslope and hollow (Jasiewicz & Stepinski, 2013). Input data for geomorphons are of raster character (DEM), as well as scale parameters (Frankl et al. 2016). The 30 m DEM was used for the analysis (SRTM). Among the scale param-

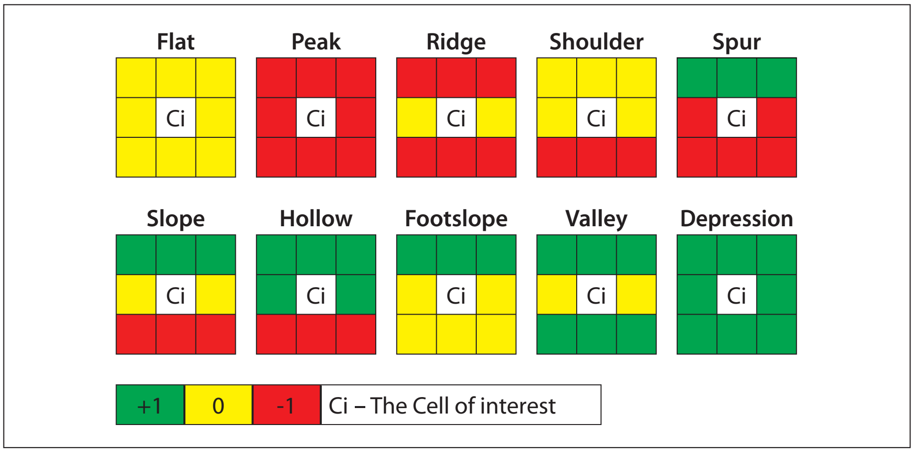

Figure 3: Geomorphons for the most typical terrain forms (authors' design).

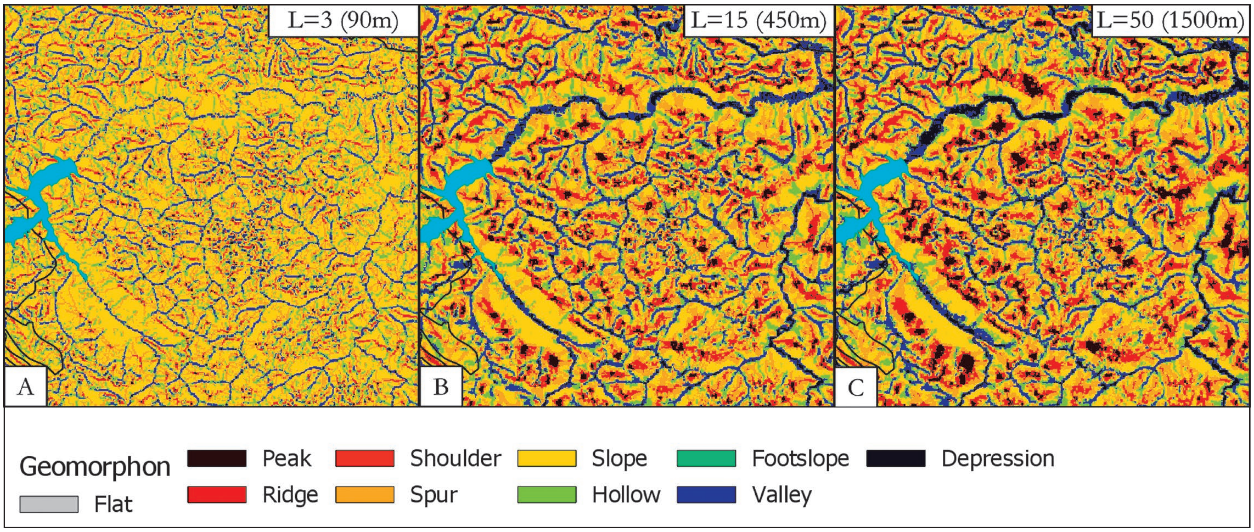

Figure 4: Geomorphons for different values of the search radius (L).

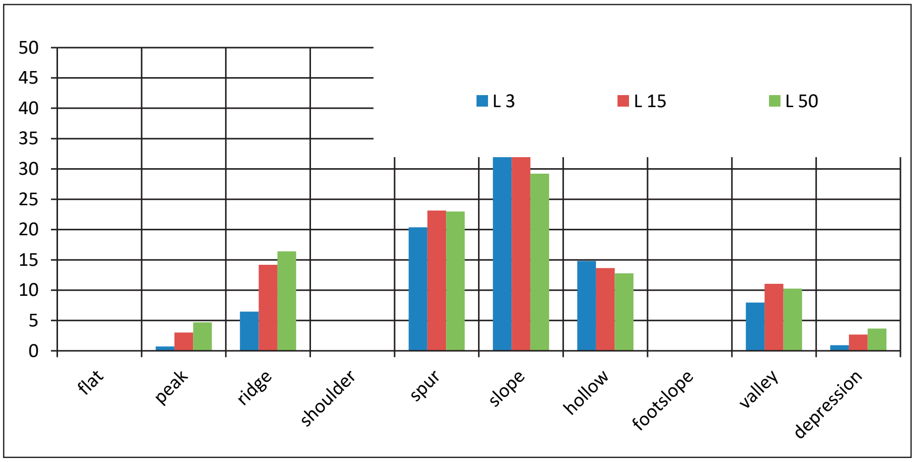

Figure 5: Distribution of geomorphons in Valjevo-Mionica karst, for search radius values (L) 3, 15 and 50.

eters, the Outer Search Radius was used (distance in meters or cells from the main cell, L) and flatness threshold (t) (Atkinson et al., 2020). Aiming to optimize the size of the search radius, comparative analysis was carried out for L=3 (90), 15 (450), 50 (1500) (Figure 5), while the value 1 was used for the flatness threshold (t). Optimization of the Outer Search Radius was carried out in order to determine the first-order landforms within which the dolines are present as second-order landforms.

4. RESULTS

Dolines are present on 75% of the Valjevo-Mionica karst area, where the total of 5319 positions was mapped. Figure 6b shows the overview of their spatial distribution descriptive statistics. The central tendency point, with the coordinates X 7411258, Y 4897608 is situated in the Brangović village. The circle around the central tendency point has a radius which corresponds to the value of one standard deviation (standard distance). The circle encompasses 65% of the mapped dolines, which implies their normal distribution within the Valjevo-Mionica karst. The main (longer) axis of the standard deviation ellipse, which follows the direction of largest dispersion of dolines, is oriented in NW-SE direction (288°–108°) (Figure 6b).

The analysis of doline density in the studied area included three measure types. The first type, the global density (in our case, 14 dolines per km^2), shows the homogeneous distribution, regardless of the local differences, thus giving a rather poor research potential. The second measure type is the quadrat (square) density for 1 km^2 spatial units, which showed the largest values – as many as 81 dolines per 1 km^2 in Robaje village (Figure 6). According to this measure, 79% of the territory has the doline density less than 30 dolines per km^2, and only in 2% the density is larger than 50 dolines per km^2. Apart from Robaje, large doline densities are present in the villages of Rajković, Osečenica, Brežđe, Stapar and Lelić. The problem with this measure is that it shows homogenous distribution of dolines within a quadrat, not depicting the fine spatial differences. In order to show

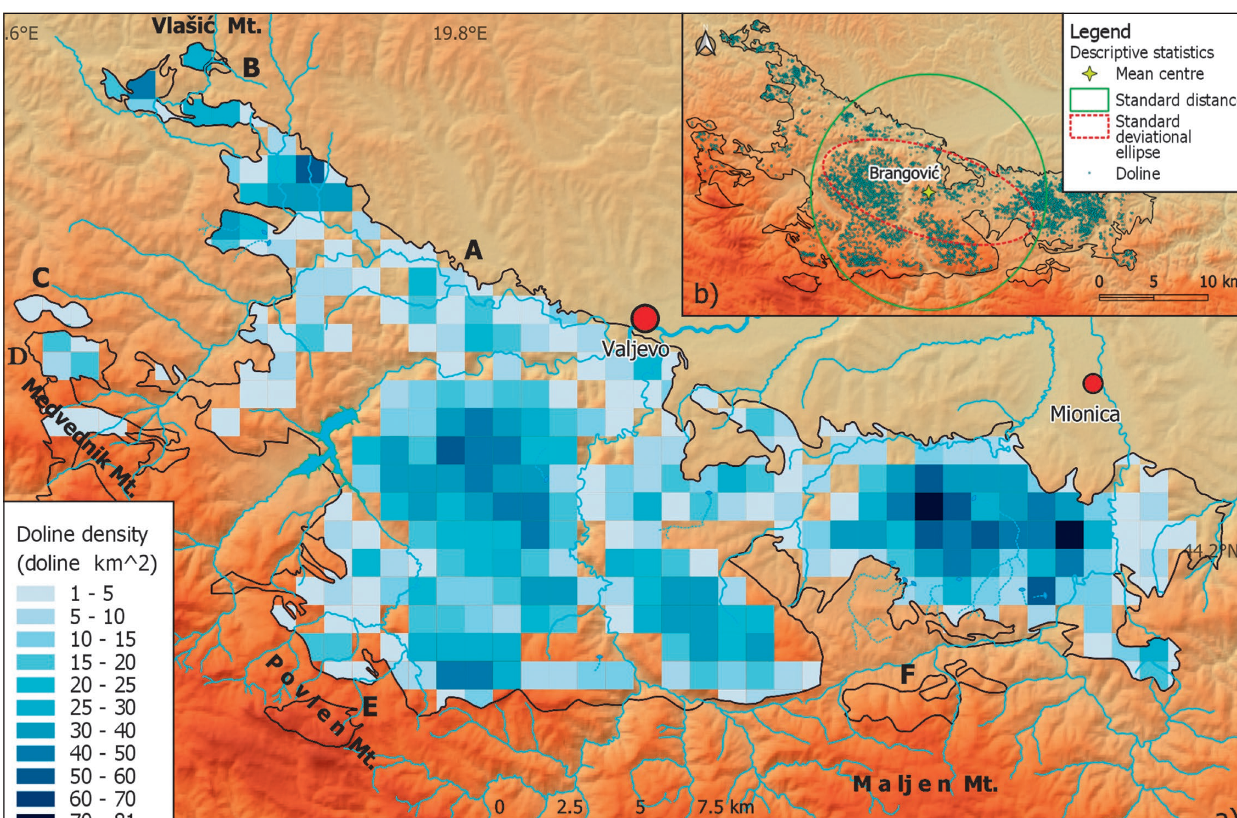

Figure 6: Quadrat (square) density of dolines in Valjevo-Mionica karst.

these differences, the third measure type is used – Kernel density. The maximum value in this type of density is 33 dolines per km^2, registered in Robaje, Brežđe and Stapar. Generally, the densities are larger in the eastern part of the research area, in comparison with the western part. The largest areas are characterised with the doline density of 2-5 dolines per km^2 (28.6 %), followed by the areas with 5-10 dolines per km^2 (26%), and finally 1 doline per km^2 on 21.6% of the total area. The areas with very high doline density, 25-33 per km^2 are the least represented, taking only 1% of the total area. These zones are spatially fragmented, stretched along the direction NW (Stapar) – SE (Robaje) (Figure 7).

In Valjevo-Mionica karst, three spatial clusters with largest number of dolines may be differentiated. The clusters include 34% of the total territory, with 72% of the total number of dolines. These regions are divided by canyon valleys of the rivers Sušica/Jablanica, Gradac, Lepenica and Ribnica. Two of these regions have been previously named as Lelić and Bačevci karst. The third

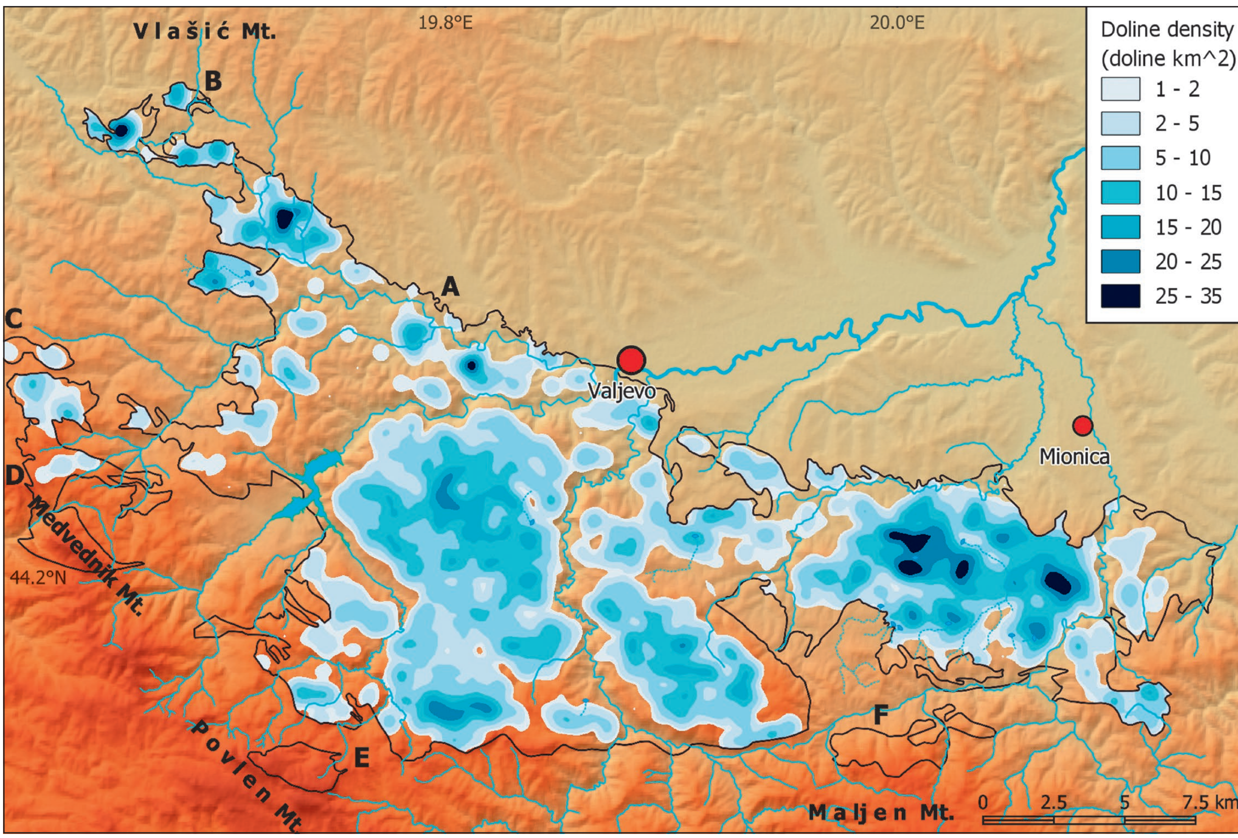

Figure 7: Kernel density of dolines in Valjevo-Mionica karst.

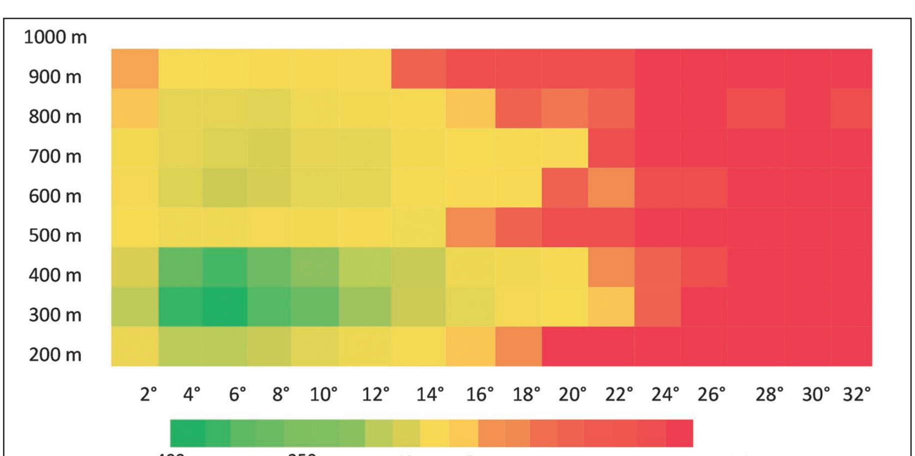

Figure 8: Distribution of dolines in Valjevo-Mionica karst by elevation and mean slope, presented as the heat map.

karst region, with largest densities of dolines in all measure types is the Robaja karst (Figure 9).

As previously determined in many publications, the slope of the topographic surface plays a significant role in spatial distribution of dolines (Telbisz et al., 2007; Pahernik, 2012; Artugyan & Urdea, 2016; Lončar & Grcić, 2022; Mihevc & Mihevc, 2021). In Valjevo-Mionica karst, the dolines are situated in the slope interval from 0° to 22° (Figure 8). With the increase of the slope, the number of dolines decreases. Out of the total number of dolines, 96% are situated on the mildly inclined slopes, up to 12°. On the slopes exceeding 20° there are only 13 dolines (less than 1%).

Judging by the Kernel density, the number of dolines

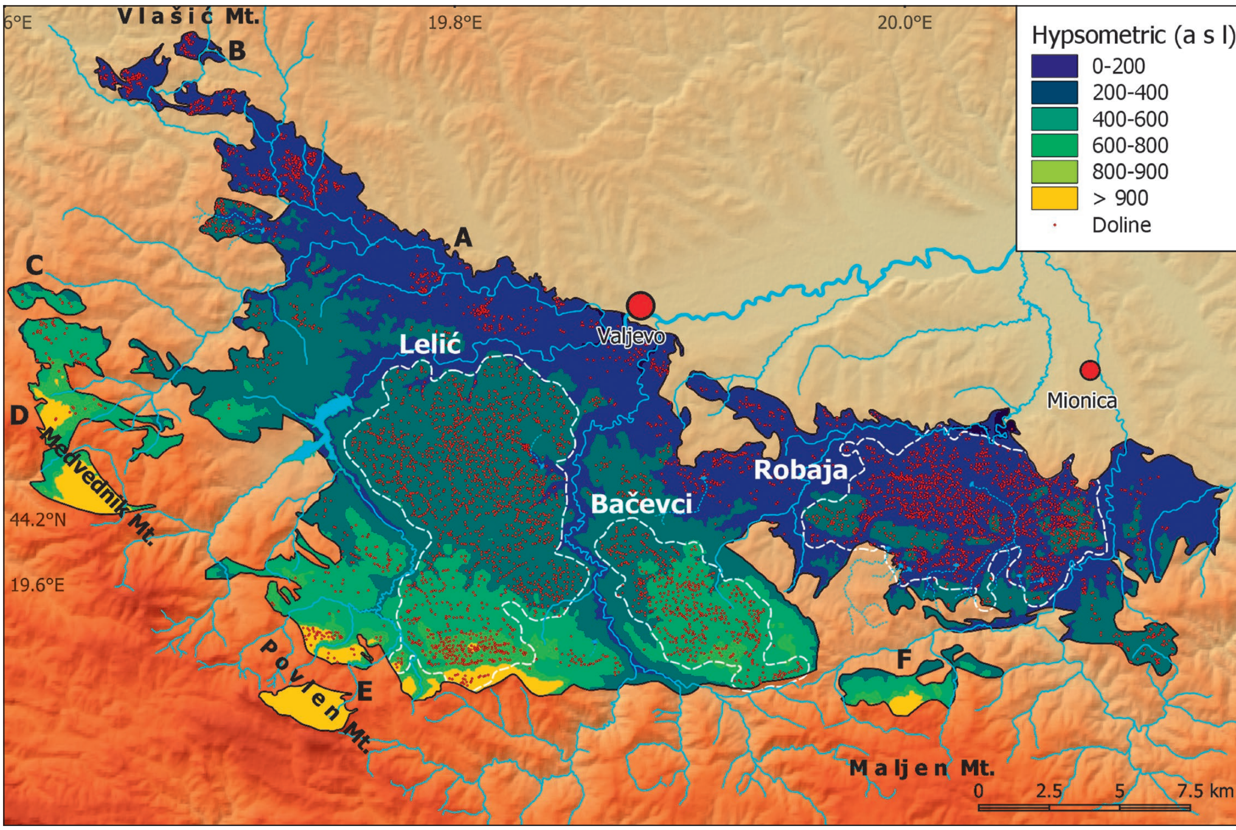

Figure 9: Elevation distribution of dolines in Valjevo-Mionica karst.

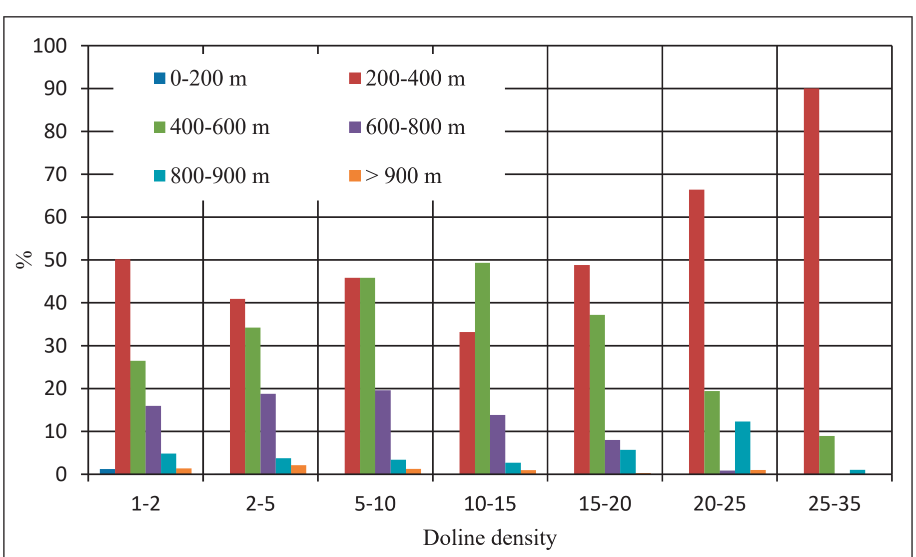

Figure 10. Distribution of doline densities in the elevation belts.

per km² decreases with slope increase. The average slope of the topographic surface with 1 doline/ km² is 10° (in the interval 6° to 19°). For the density of 6 dolines/km², the average slope is 8° (interval 2° to 13°), while the average slope for the densities exceeding 15 dolines/km² is 5° (1° to 12° interval).

There are seven elevation belts in the Valjevo-Mionica karst with the spans of 200 m and 100 m. The lowest point lies within the zone where the Lepenica River leaves the karst area (at 160 m a.s.l.), while the highest one is the top of the Povlen Mt at 1301 m (Figure 9). Dolines are concentrated in the elevation belt from 187 m and 988 m. Most of the dolines are situated between 200 m and 400 m a.s.l. (42%) and 400 m to 600 m (40%). There is only one doline below 200 m (in the Lepenica River valley), while 79 dolines are situated at the elevations higher than 900 m (north-eastern slopes of Povlen Mt. and Medvednik Mt). The areas with the highest Kernel densities (25-35 dolines per km²) are dominantly situated in the elevation span from 200 m to 400 m a.s.l. Other areas are present at the elevations 400 m to 600 m (9%) and 800 m to 900 m (1%). There are areas of 20-25

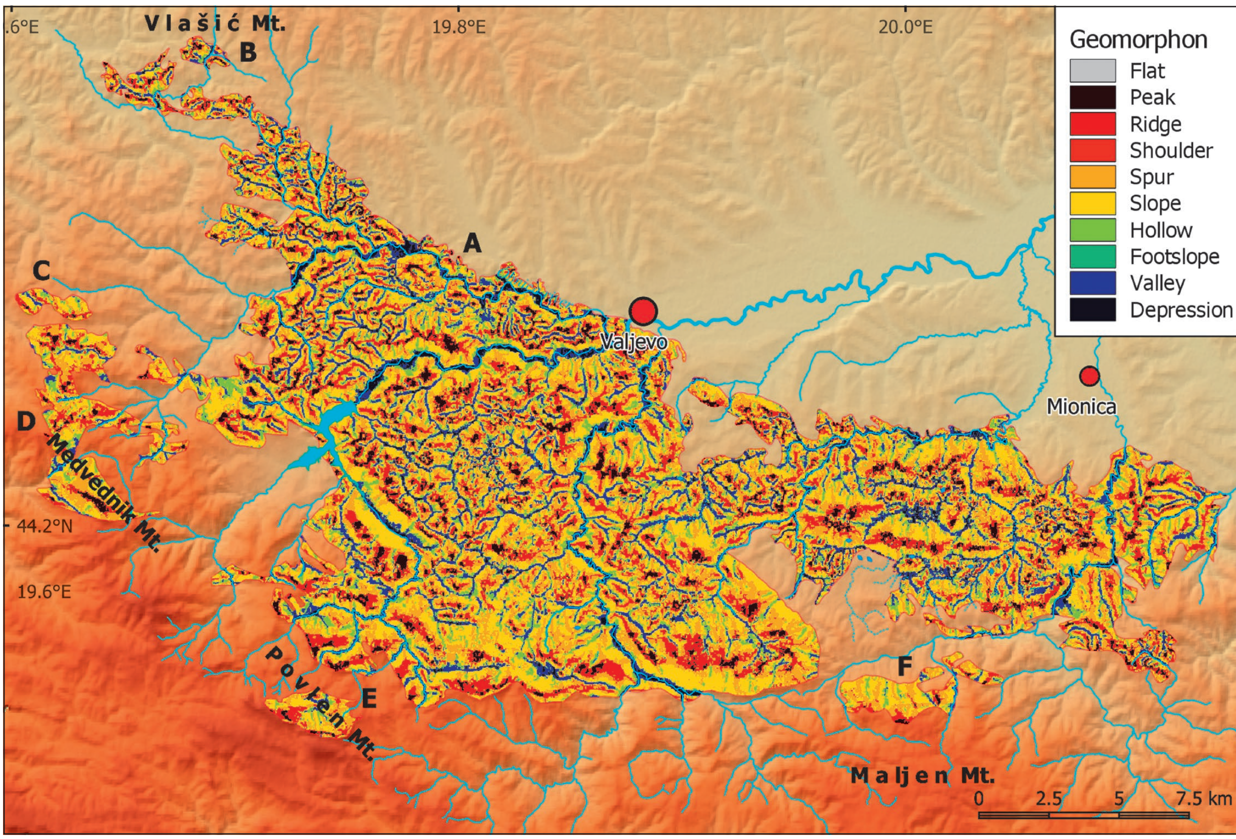

Figure 11: Geomorphons of Valjevo-Mionica karst (L=50).

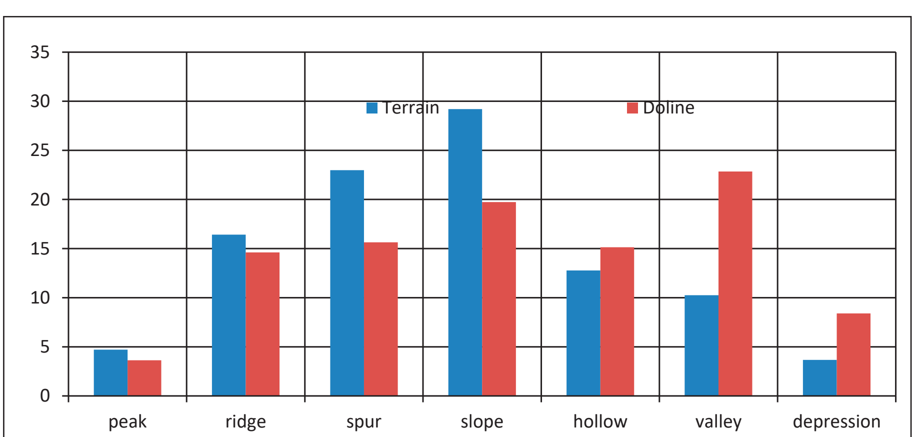

Figure 12: Geomorphon structure of Valjevo-Mionica karst and the dolines on particular units.

dolines per km^2 in the elevation belt between 800 m and 900 m a.s.l. (Figure 10).

Using the geomorphon method, relief of the Valjevo-Mionica karst was defined by the values of the Outer Search Radius values of 50 cells (L=50) and flatness threshold (t), value 1. Input data refer to the 30 m resolution DEM, meaning that the generated relief elements have the length up to 1500 m. The structure of geomorphons does not show three elements: flat, shoulder and footslope (Figure 11). Other elements are present with various percentages. The most dominant are slope (29%) and spur (23%). The least present elements (below 5%) are depression (3.5%) and peak (4.5%). Dolines are situated in geomorphons corresponding to valley (23%), slope (19.5%), spur (15.5%), hollow (15%), ridge (14.5%), depression (8.4%) and peak (3.5%). Structure of geomorphons within which the dolines are formed is not a consequence of the total geomorphon structure of the Valjevo-Mionica karst, because the correlation between the mentioned values is not significant (Figure 12).

5. DISCUSSION

Spatial variability of karst dolines is present in the area of Valjevo-Mionica karst. It may be caused by lithological composition, tectonic pattern, relief, climate, etc. (Öztürk et al., 2018). This paper primarily focuses on the impact of relief to the spatial distribution of dolines. The relevant elements are morphometry (surface slope) and elevation. Landform analysis is based on digital classification based on geomorphons. The input data for both mentioned geomorphological characteristics were digital elevation models with the resolutions of 90 m (for morphometry) and 30 m (for morphology).

Regarding the slopes of the areas with dolines occurrence, Valjevo-Mionica karst confirms that the number and density of dolines is inversely related with the increase of slopes, due to the relation between surface and underground runoff. In the study area, the slope interval of doline occurrence is between 0° and 22°. Several publications report that the slopes of surfaces populated by dolines have a considerably larger span, from 0° to almost 32°-35°, such as in the Dinaric karst (Pahernik, 2000; Marković et al., 2016, Lončar & Grcić, 2022), Carphatian Mts karst (Artugyan & Urdea 2016), and Missouri, USA (Orndorff et al. 2000). The insight to the input data for these localities shows that DEMs of higher resolutions (30 m) were used. In the case of Valjevo-Mionica karst, after testing the options for 30 m DEM vs. 90 m DEM, we opted for a smaller resolution (DEM 90 m) for the purpose of general surface slope determination, because it turned out to be smoother, without the imprints of particular dolines to the slope of the overall area. Similar choices and conclusions were applied by Telbisz et al. (2007) for the karst of Mt. Miroč (Serbia), Faivre and Pahernik (2007) for Brač Island (Croatia) and Mihevc & Mihevc (2021) in Slovenia.

In Valjevo-Mionica karst, the significance of elevation for the doline occurrence was not clearly detected. The largest number of dolines, as well as the largest density (33 dolines per km^2), was detected in the elevation belt 200-600 m a.s.l. Marković et al. (2016) pointed to the genetic significance of elevation for doline development (increased densities), in terms of microclimate conditions), while Milošević et al (2022) pointed to tension joints on top of anticline crests (comparable to Tîrlă and Vijulie, 2013).

At the level of morphostructures, dolines are "secondary" landforms, occurring on (or within) first-order landforms, such as mountain plateaus, levelled surfaces, large depressions (uvalas, poljes), etc. Hydrographical and morphometric characteristics of these landforms may stimulate or modify formation and development of dolines. This study uses geomorphons as the indicators for the analysis of morphological characteristics of the research area and particularly on the distribution and density of dolines.

In order to get a better insight to the relation between dolines and geomorphons, we introduced grouping of elements following a runoff criterion – wheter the water converges towards a geomorphon or diverges from it. Using this criterion, it is possible to group three categories: (1) concave (valley, depression, hollow), (2) convex (spur, ridge, peak) and (3) slopes. 47% of the research area belongs to the first category, 33.5% to the second and 19.5% to the third. Concave geomorphons correspond to pocket valleys (cf. Lipar & Ferk, 2015), blind valleys, dry valleys; convex geomorphons correspond to ridges/divides, while slopes mostly refer to long valley sides. In case of Valjevo-Mionica karst, almost 50% of dolines are situated along concave geomorphons, mostly on bottoms (thalwegs) of former fluvial valleys, as opposed to the cases typical for karst plateaus (Orndorff et al., 2000, Artugyan & Urdea, 2016). Smaller valleys transformed to dry valleys, blind valleys and hanging valleys, transforming the environment to typically karstic (Lazarević, 1988). Former thalwegs became the locations of lined-

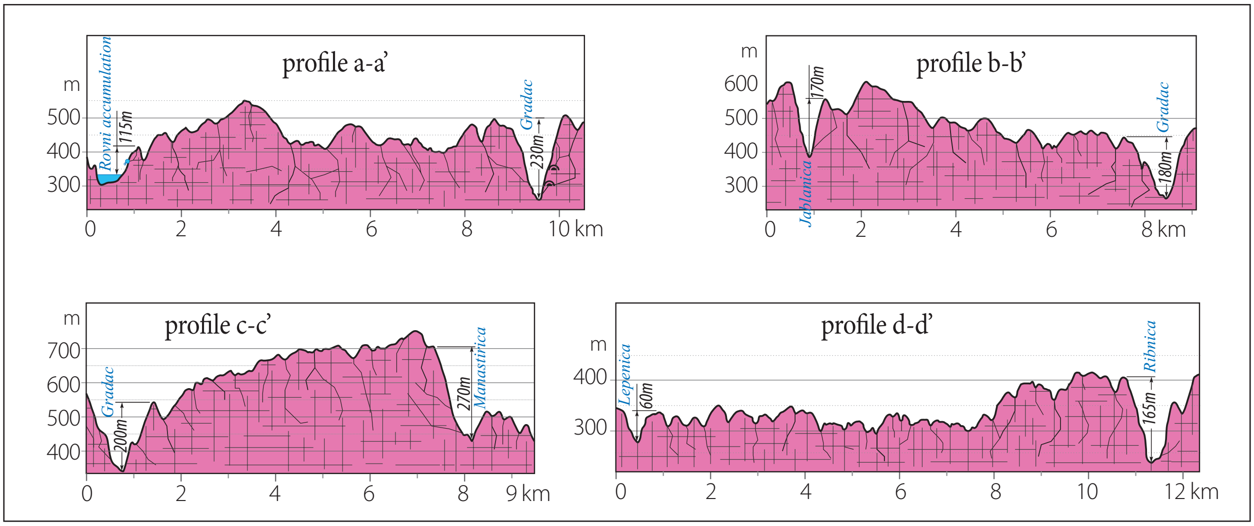

Figure 13: Canyons of the rivers Jablanica, Gradac and Ribnica, which divide Lelić karst (a-a', b-b'), Bačevci karst (c-c') and Robaja karst (d-d'). Gray lines symbolize fractures and bedding (as artwork). Profiles are indicated on Figure 1.

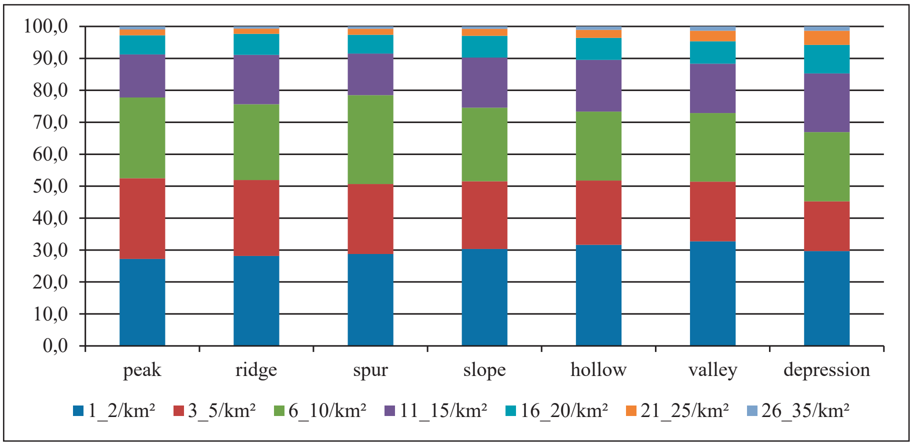

Figure 14: Doline density distribution in particular types of geomorphons.

up dolines, phenomenon which was observed by Cvijić (1912) as well. The mentioned characteristics point to the advanced stage of karstification (Bočić et al., 2016; Petrović et al., 2016). As mentioned before, dolines of Valjevo-Mionica karst are mostly grouped to three spatial clusters – Lelić karst, Bačevci karst and Robaja karst, divided by canyons of allogenic rivers. The results of the study indicate that the karst area initially had a fluvial development phase. With the increase of the hydraulic gradient and drop of the groundwater levels, only allogenic rivers managed to keep their activity, by the process of incision and formation of canyon valleys. Deep incision up to 270 m (at the location Manastirica/Ribnica and somewhat less elsewhere) resulted in intensification of the karst process.

Doline density is in accordance with the interpretation of geomorphons, especially within the depressions. Depression geomorphons indicate the places of dry valleys confluences, adding also to the radial distribution of dolines apart from linear.

6. CONCLUSIONS

Following the aims of the study given in the introductory chapter, the conclusions are related to (a) proper naming of the study area following the geographic naming conventions, (b) methodological issues, (c) numbers and spatial patterns of dolines, (d) terrain slope issues, and (e) morphostructures.

- Naming of the study area followed the principles of the spatial extent of karstified limestones on one hand,

and the existence of the formal administrative units (municipalities of Valjevo and Mionica) on the other hand. Instead of the former naming of this karstic area as Valjevo karst, the appropriate naming is Valjevo–Mionica karst. The total area size is 380 km^2.

- The determined total number of dolines (5319) cannot be considered as absolutely exact, due to the technical limitations of the main data source – the topographical map 1:25.000 – in which the depressions of less than 2.5 m depth are not visible. However, the advantage of the maps in this scale is that the content is not generalised, meaning that their relative spatial relations are preserved. Consequently, the density of dolines, as well as their uneven distribution, may be considered correct and reliable. Higher resolution DEMs do not necessarily provide better detection of the number of dolines, but only the higher accuracy. For particularly high resolutions (1 m), the criteria for doline detection are difficult to determine (Mihevc & Mihevc, 2021; Utlu & Öztürk, 2023, Telbisz et al., 2024).
- Detected dolines in Valjevo–Mionica karst are unevenly distributed. The chosen indicator was Kernel density measure in the search radius of 568 m, showing 33 dolines/km^2 in the Stapar village and 31 dolines/km^2 in the villages of Brežđe, Rajković and Robaje. The dolines are grouped in three clusters – Lelić, Bačevci and Robaje, where 34% of the total karst areas host as much as 72% of the total number of dolines.
- Despite the lithological and climatic homogenity within Valjevo–Mionica karst, doline distribution is heterogenous. In many existing literature sources, this is explained as a tectonic control of dolines distribution (Faivre 1992; Faivre & Reiffsteck, 1999, 2002; Faivre & Pahernik 2007; Öztürk et al., 2018 a,b). As opposed to that kind of interpretation, our study area reveals the significance of topographic slope and the degree of morphological and hydrographical evolution of the surrounding river valleys. As for the topographic surface slope, 96.5% dolines are situated on the surfaces up to 12°, maximally up to 22°. Morphological evolution of the area is characterised by the intensive karstification, resulting from the fast incision of allogenic rivers, thus inducing high hydraulic gradients within the karst aquifers. Geomorphological outcomes are visible as dry valleys, blind valleys and hanging valleys, while the previous thalwegs are dotted with lined-up dolines. Out of the total number of dolines, 47% are situated at the bottoms of dry valleys.
- The areas of highest doline densities (25-33 /km^2) are not directly related to surface morphology. Their orientations in the NW–SE direction point to the structural characteristics corresponding to the Dinaric pattern.

ACKNOWLEDGEMENT

This research was supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia (Contract No. 451-03-66/2024-03/200172).

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