COBISS: 1.01, DOI:10.3986/ac.v51i1.10465

GIS-BASED ANALYSIS OF DOLINE DENSITY ON MILJEVCI KARST PLATEAU (CROATIA)

ANALIZA GOSTOTE VRTAČ Z ORODJI GIS NA KRAŠKI PLANOTI MILJEVCI (HRVAŠKA)

Nina LONČAR[1*] & Ivana GRCIĆ[2]

Abstract UDC 551.435.82:659.2:004:91(497.581.2)
Nina Lončar & Ivana Grcić: GIS-based analysis of doline density on Miljevci karst plateau (Croatia)
The doline density and their spatial distribution analysis is one of the methods used for karst relief morphostructural analysis. We present the results of morphometric features, doline spatial distribution and their relationship on Miljevci karst plateau based on digital elevation model (DEM). Altogether, 286 dolines were mapped in the study area. The doline density analysis has been applied. The results show that the doline spatial distribution is clustered. Two larger areas with densities of 30 and 34 dolines/km^2 are determined. Their distribution along the river canyons could indicate the existence of a palaeodrainage network. The strongest link between the doline density and topography is with inclination and vertical relief dissection, whereas the number of dolines decreases with an increase of slope inclination and relative relief. Such distribution confirms the suitability of karstic plateaus without active drainage for doline formation.
Keywords: karst, doline density, geomorphometry, GIS, Croatia.

Izvleček UDK 551.435.82:659.2:004:91(497.581.2)
Nina Lončar in Ivana Grcić: Analiza gostote vrtač z orodji GIS na kraški planoti Miljevci (Hrvaška)
Analiza gostote vrtač in njihove prostorske razporeditve je ena od metod, ki se uporabljajo za morfostrukturno analizo kraškega reliefa. Avtorici predstavljata rezultate morfometričnih značilnosti, prostorske razporeditve vrtač in njihove povezanosti na kraški planoti Miljevci na podlagi digitalnega modela višin (DEM). Skupno je bilo na proučevanem območju kartiranih 286 vrtač. Uporabljena je bila analiza gostote vrtač. Rezultati kažejo, da je prostorska porazdelitev vrtač v obliki grozdov. Opredeljeni sta dve večji območji z gostoto 30 oziroma 34 vrtač/km^2. Razporeditev teh vzdolž rečnih kanjonov bi lahko kazala na obstoj paleodrenažnega omrežja. Najmočnejša povezava med gostoto vrtač in topografijo je z naklonom in vertikalno razčlenjenostjo reliefa, pri čemer se število vrtač zmanjšuje z večanjem naklona pobočja in relativnega reliefa. Takšna porazdelitev potrjuje primernost kraških planot brez aktivne drenaže za nastanek vrtač.
Ključne besede: kras, gostota vrtač, geomorfometrija, GIS, Hrvaška.

[1] Nina Lončar, Geospatial Analysis Lab, Department of Geography, University of Zadar, Trg Kneza Višeslava 9, 2300 Zadar, Croatia, e-mail, ORCID: nloncar@unizd.hr, https://orcid.org/0000-0003-0795-2832
[2] Ivana Grcić, Stonemasonry school Pučišća, Novo riva 4, 21412 Pučišća, Croatia
* Corresponding author

Received/Prejeto: 10.2.2022

1. INTRODUCTION

Karst plateaus are peculiar polygenetic karst forms developed on carbonate terrain (Ford & Williams, 2007). These wide flattened karst areas are (generally) characterized by poor surface dynamics and are sometimes dissected by dolines and canyons of the allogenic rivers (Bočić et al. 2010, 2015). Morphogenetic and morphometric research is important in understanding karst geomorphic evolution and has been the focus of numerous studies. Knowing the nature and the factors that are controlling dissolution processes in karst soluble rocks and drainage as a result of these processes (Ford & Williams, 2007) allows better understanding of karst topography. Dolines are considered to be among the most prominent and representative geomorphic features of karst landforms; therefore, they are a great indicator of a karstification process. Corrosion, collapse, suffusion and bending dolines are defined by the dominant process involved in their formation (Ford & Williams, 2007). The doline spatial distribution analysis is one of the methods used for karst relief morphostructural analysis. The intensity of their occurrence, shape, dimensions shows a strong connection with pre-existing lithological structures, tectonic and hydrogeology features, and specific microclimate characteristics (Faivre, 1992; Ford & Williams, 2007; Pahernik, 2012; Sauro, 2016). Consequently, they are of great importance in the tectonic and geomorphologic study and palaeoenvironmental reconstructions of karstic regions (e.g., Faivre, 1994; Mihljević, 1994; Plan & Decker, 2006; Mihevc, 2007; Faivre & Pahernik, 2007; Sauro et al., 2009; Gabrovšek & Stepišnik, 2011; Ballut & Faivre, 2012; Daura et al., 2014; Šušteršič, 2016; Öztürk et al., 2018; Tîrlă et al., 2020). Also, due to their relationship with subsurface features like epikarst, dolines are important connection between surface and underground drainage systems. Their distribution strongly influences the outcomes of groundwater vulnerability maps, subsidence risk and land use studies as well as mapping for environmental and hydrological management strategies (Moreno-Gómez et al., 2019).

Nowadays, the use of geomorphometry for mapping and modelling of natural landscapes, at regional and local scales is essential (Artugyan & Urdea, 2016). Most common input for geomorphometric analysis, is a digital elevation model (DEM), a rectangular array of surface heights (Pike et al., 2009). There are variety of geographic information system (GIS) based studies using DEMs in karstic areas worldwide (e.g., Telbisz et al., 2007, 2011; Tagil & Jenness, 2008; Siart et al., 2013; Gallay et al., 2015; PardoIgúzquiza et al., 2016; Artugyan & Urdea, 2016; Hofierka et al., 2017; Silva et al., 2017; Meng et al., 2018; Moreno-Gómez et al., 2019; Mihevc & Mihevc, 2021).

In Croatia, there are around 350000 recorded dolines, predominantly distributed in the Dinaric region whereas Gorski Kotar is densest area (242 dolines/km^2) (Pahernik, 2012). They mainly form doline fields and long rows along contacts, on fractures, joints and smaller faults (Bognar et al., 2012). Characteristics and spatial distribution analysis of doline density revealed that lithology, tectonic structure and relief morphometric characteristics have large impact on doline formation and distribution (Faivre, 1992, 1995; Mihljević, 1994; Pahernik, 2000; Faivre & Bocquet, 1999; Faivre & Reiffsteck, 1999, 2002; Faivre & Pahernik, 2007; Telbisz et al., 2009; Bočić et al., 2010; Buzjak, 2011; Pahernik, 2012; Marković et al., 2016). Some of these works contributed also to a modern digital modelling of relief and to use of GIS in digital analyses and visualization of spatial data in geomorphic research.

So far, geomorphologic research in area of Miljevci plateau has been related to the Krka River composite valley. Friganović (1961) described in detail the poljes of upper river basin (Petrovo, Kosovo and Knin polje) while Perica et al. (2005) studied the slope processes and zoogenic features of the Krka valley and its river basin from Knin to Bilušić buk. The object of this study is determination of the general geomorphologic characteristics of Miljevci karst plain based on digital elevation model (DEM). Knowing that gentle slopes of karstic plateaus without active drainage make favorable topographic conditions for doline formation (Gams, 2000; Plan & Decker, 2006; Faivre & Pahernik, 2007; Sauro, 2013; Daura et al., 2014; Bočić et al., 2015), we aim to (1) validate the suitability of the Mliljevci karst plateau for doline formation, (2) determine the number and spatial distribution of dolines and (3) explain their morphogenetic context.

2. STUDY AREA

Miljevci plateau is part of North-Dalmatian karst plateau between Krka and Čikola River (red line on Figure 1) in Šibenik-Knin county (Croatia). It refers to the seven villages that administratively belong to the Drniš municipality (Bogatići, Brištane, Drinovci, Kaočine, Karalići, Ključ and Širitovci) located along the middle course of the Krka river (Figures 1, 2). The research area of 264.89 km^2 was arbitrarily defined by combining natural features and spatial boundaries of the aforementioned villages. The boundary is represented by Visovac Lake and the upper Krka River to the east and south-east, by Torak Lake and Čikola River to the south and south-east, and administrative borders of the aforementioned villages to the north and north-east. In morphological sense, three parts are covered: the canyon of Krka and Čikola in the hypsometric class up to 200 m a.s.l., the plateau 200 to 300 m a.s.l. and NE part above 300 m a.s.l. (Figures 1, 2).

According to geotectonic regionalization of the Dinaric area, the microregion Promina-Miljevci belongs to the external Dinarides zone along the Promina-Moseć-Muć fault (Bognar et al., 2012.). The Knin, Kosovo and Petrovo karst poljes margins mostly represent the tectonic boundary of Adriatic and Dinaric platforms in the wider area of the North-Dalmatian Plateau (Grimani et al., 1975, Polšak et al., 1990, Perica et al., 2005).

The territory is characterized by elongated parallel geomorphic features stretching in NW-SE (Dinaric) direction. The geomorphic features are formed of Cretaceous and Paleogene rocks with numerous normal and reverse faults that have influenced the surface morphology formation (Figure 3). The Krka River mostly intersects geological structures. A NW-SE fault is separating the area into two hypsometric units; flat (up to 300 m a.s.l.) and higher NE (> 300 m a.s.l.). The entire area is characterized by a series of NW-SE trending folds. Parallel anticlines and synclines consist of alternating layers of foraminiferal limestone, conglomerates and Cretaceous sediments (Mamužić, 1971; Ivanović et al., 1977). Carbonates dominate in the valleys of the Krka and Čikola Rivers. The oldest deposits are Upper-Cretaceous limestones with dolomite layers (Turonian-Senonian) in anticlinal core. They are stretched in the NW-SE direction in three elongated zones. The first zone extends in the narrow belt from Ključ to Drinovci. The second zone

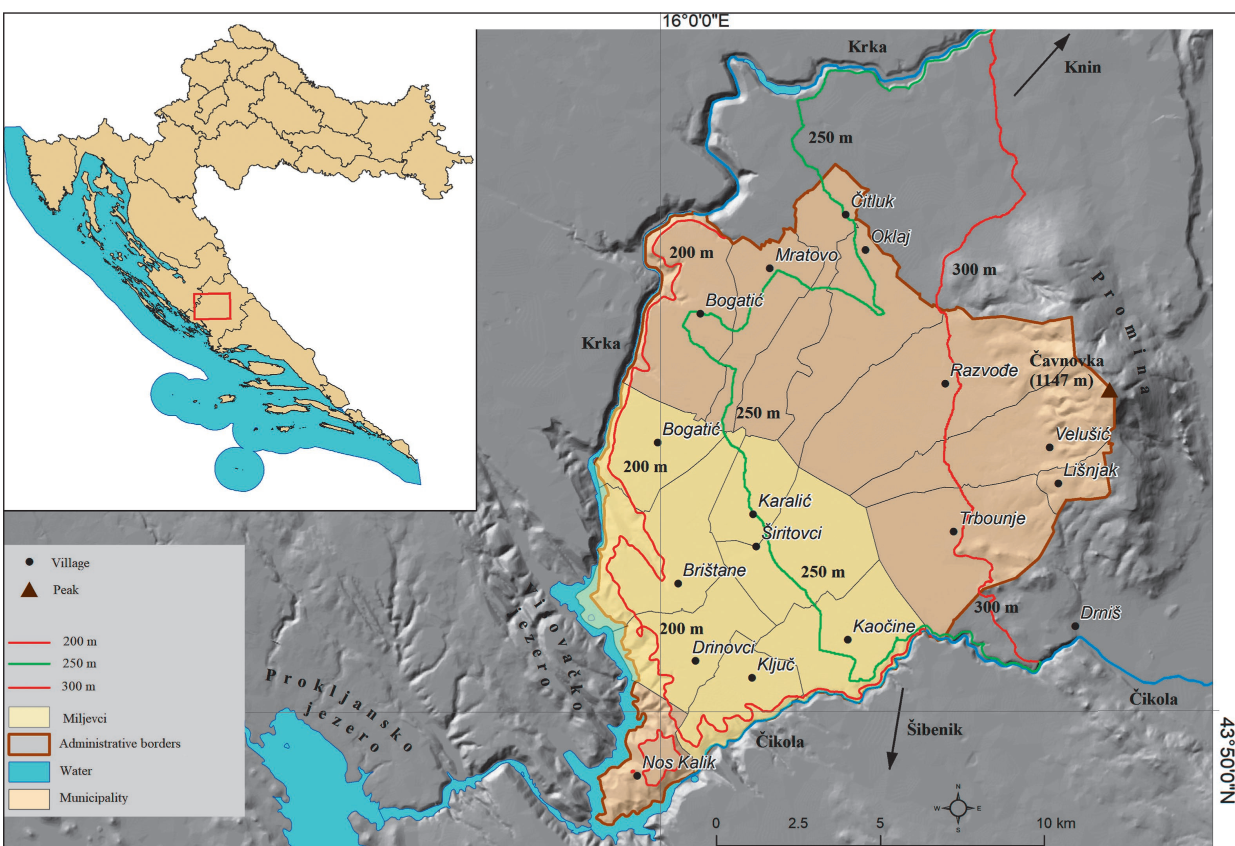

Figure 1: Geographic location of the research area.

has a central position in relation to the other two, it is the largest and extends from Trbounje to Bogatić. The northernmost zone of Upper-cretaceous limestone, covers the area from Velušić to Oklaj. The erosion-discordance boundary to the Upper-Cretaceous rocks in this area consists of Eocene limestone alternating with marl and conglomerate (Ivanović et al., 1977). The youngest stratigraphic units consist of Quaternary *terra rossa* mixed with breccia and products of marl erosion (Vedrovo polje, Bilo polje, Oklajsko polje), tufa, alluvium and diluvium (Buzjak et al., 2013; Kruk et al., 2014). The flood material along the Krka river consists of sand, silt and sludge. There are rare and isolated phenomena of deluvial breccia mixed with the soil on the older Paleogene deposits (Ivanović et al., 1977). In the northern part of the researched area, the largest part of the Paleogene sediments consists of Promina conglomerates, breccias, marls, bauxite and limestones with fragments of fossil remains of bivalve molluscs (Figure 4). These are Upper-Eocene Promina marine sediments deposited in the last phase of Paleogenic emersion (Velić & Vlahović, 2009).

Geomorphologically, the Miljevci Plateau is a microgeomorphic regional unit within the larger subgeomorphic region of the *North-Dalmatian Plateau*. Promina Mountain range is subgeomorphic regional unit within macrogeomorphic unit of *Northwest Dalmatia with archipelago* (Bognar, 2001). The largest orographic unit is Promina, a mountain of elliptical shape elongated in the north-south direction with the highest peak Čavnovka of 1147 m height. However, most of the area is a high karst plain in the macro scale, which is a highly flat area in the macro scale and much more vertically dissected relief in the micro scale. The North-Dalmatian Plateau has developed deep karst with characteristics of thicker carbonate layers. Between east and west, the plateau narrows southwards and forms a triangular shape between the Krka and Čikola rivers. This part is believed to be the most resistant area of the North-Dalmatian plateau as it is located on pure Upper-Cretaceous limestone (Roglić, 1957).

Miljevac area belongs entirely to the Csa climate (Filipčić, 2000). The annual temperature and precipitation trend is inverse. In the warm part of the year there is a maximum of temperature and a minimum of precipitation. Therefore, the Miljevac area is characterized by a maritime regime of annual precipitation colder, but wetter. According to climatic data from Šibenik and Drniš stations (CMHS, 2019) the average annual rainfall is 845 mm and it rises with strengthening of continentality; from Šibenik (750 mm) towards Drniš (940.1 mm) and further towards Knin. The average annual air temperature in the plateau area varies from 13.5 °C to 16.5 °C, respectively. The prevailing winds are NE *bora* and SE *sirocco*. Unfavorable annual course of precipitation and high summer air temperatures, continuous windiness and frequent storm surges, as well as the predominance of water-permeable carbonate bedrock cause large losses by evaporation and regular and prolonged drought, which destabilizes the pedological cover and bare terrain.

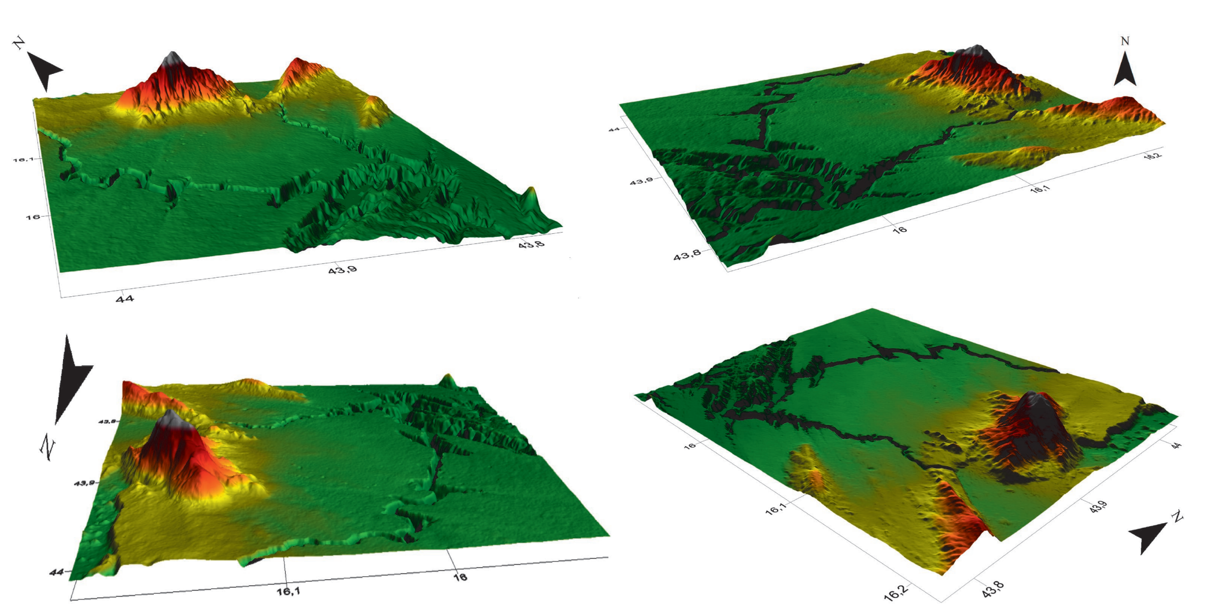

Figure 2: Perspective overview of relief in the research area.

3. METHODS

The *Digital Elevation Model over Europe* (EU-DEM) was selected for creation of digital elevation model (DEM), which is used for further analysis. The data are in GeoTIFF format (the reference ellipsoid is WGS84) and the spatial resolution of the base is 25 m (EU-DEM, 2018). ArcGIS 10.1 software package and *Surfer* software program were used to create perspective three-dimensional terrain visualization. DEM of the raster GRID structure was used for quantitative analysis of basic morphometric parameters (hypsometry, slope and vertical relief dissection) as an input raster. HTRS96 projections were used for visualization of parameters and map making (reference geoid is GRS 1980). The hypsometric map was produced in combination of contour lines, shading and the corresponding color scale. The hypsometric analysis separated nine height classes ranging from 42 to 1147 m above sea level. For visibility and clearer analysis, the number and range of hypsometric classes were determined arbitrarily according to the minimum and maximum elevation of the area taking into account the size and morphology of the investigated area. Slope inclination was obtained using *Slope* tool algorithms (Horn's method) and DEM height data. Slope categorization is based on standardized processes activated on each slope grade and has six categories: 0-2°, 2-5°, 5-12°, 12-32°, 32-55° and >55° (Table 2). The absolute value of vertical relief dissection was obtained using the raster calculator. Raster with maximum and minimum elevation values were calculated with the *Focal Statistics* tool *(Spatial Analyst)* using the circle as the neighbourhood shape and cell size 3x3[1]. This tool performs a neighborhood operation that computes an output raster, where the value for each output cell is a function of the values of all the input cells that are in a specified neighborhood around that location. For the determination of certain macro and meso geomorphic phenomena, 1:5000-scale digital orthophoto, 1:25 000-scale topographic, and 1:5000-scale State Geodetic Administration Croatian basic maps were used from the geoportal of the Republic of Croatia. In the last phase, the spatial distribution and density of the dolines were analysed according to the methodology used by Faivre (1992) and Pahernik (2000, 2012.). Vectorization of the dolines from the 1:25 000-scale topographic and the 1:5000-scale Croatian basic maps has created a spatial database for further quantitative analysis of dolines distribution in relation to geomorphometric parameters and lithostratigraphic features. As the first step in the last phase, all dolines bottoms were mapped, providing a database with point entities on the number and spatial distribution within the investigated area. All concave profiles, regardless of their size, depth and shape, have been digitized from the topographic map (1:25,000) and the Croatian basic map (1:5,000). One point represents the bottom of a doline. In this way, 286 dot samples were collected in the spatial database. The point density of the dolines within the circle surface of 1 km^2 was calculated using the kernels' algorithm for density. According to Pahernik (2012) several classes of density per km^2 can generally be derived: negligible density (1-10 dolines/km^2), small (10-30 dolines/km^2), medium (30-60 dolines/km^2), large (60-100 dolines/km^2), very high density (100-200 dolines/km^2) and extremely high density (> 200 dolines/km^2).

4. RESULTS AND DISCUSSION

4.1. ANALYSIS OF MORPHOMETRIC RELIEF PARAMETERS

The hypsometric analysis shows that the research area is karst platou which mostly belongs to a narrow elevation zone of 200-300 m (Table 1). The 200-500 m hypsographic class range was by far the most prevalent (87%), followed by the < 200 m class of the lowlands around river streams (8%), and 500-1500 m class of the lower mountain range occupying the north-east part of the research area (5%).

The spatial distribution of hypsometric classes indicates proper alteration of height classes stretching in NW-SE (Dinaric) direction (Figure 3a). The karst plateau with elevation 200 -300 m represents most of the research area. In the macro plan, the area is extremely flat and partially disintegrated with isolated dolines. Deeply (up to 170 m) incised canyons of Krka and Čikola riv-

[1] There is no universal method and algorithm to calculate the vertical relief dissection. The output values vary depending on the spatial resolution that is used. By comparing maximum values and resolutions, the maximum value of vertical dissection was increased by increasing the number of pixels and vice versa (Šiljeg, 2013). For example, for cell size 3x3, the maximum value is 168.62 m and for 5x5 243.67 m.

ers intersect the karst plateau. They belong to elevation range up to the 150 m with several smaller hills along the southwestern edge of the plateau towards Visovac Lake (Vitrenjača 221 m a.s.l., Glavica 199 m a.s.l., Pojatir 166 m a.s.l.). The height of these bordering hills decreases from north to south.

Table 1: Proportion of hypsometric classes in total area of study area.

Hypsometric class (m)	Total area (km^2)	Proportion (%)	Relief category (%)
< 150	13.9	5.13	Lowland relief (8.29%)
150-200	8.37	3.16	
200-250	92.95	35.09	Platou (86.58%)
250-300	105.53	39.84	
300-400	22.33	8.43	
400-500	8.54	3.22	
500-700	7.74	2.92	Lower mountain range (5.13%)
700-900	3.46	1.31	
> 900	2.34	0.90	
Total	264.89	100.00	100.00

The average elevation of the area is 272 m. It is lower in the southern and central part, and highest in the northeast towards Promina Mt. Although the average elevation is rather low, there is a large elevation difference between the lowest and the highest elevation values on a relatively small surface. The lowest point is in the Krka River canyon, (42 m), while the highest elevation is the Mt. Čavnovka peak (1147 m, Figure 3a). The C-C 'and D-D' profiles are flattening at cca. 240 m and they show non-gradual drop towards the canyons of the Čikola and Krka rivers (Figure 4). Relief profiles A-A 'and B-B' indicate the presence of higher elevations in the northeast part (Promina mountain range) (Figure 4.).

Table 2: The proportion of slope categories in the researched area with dominant relief characteristics.

Slope inclination category (°)	Total area (km^2)	Share (%)
< 2	175.16	66.13
2-5	32.15	12.14
5-12	20.82	7.86
12-32	31.76	11.99
32-55	4.91	1.85
> 55	0.07	0.03
Total	264.89	100.00

The predominance of the hypsometric class from 200-250 meters and 250-300 m can be observed. These two classes occupy 198.48 km^2 or 74.93% of the total surface area. Therefore, lower hypsometric classes within the altitude range of 200-300 m dominate. Elevation of 300-1147 m is represented in 16.78% (44.41 km^2) of the study area.

The prevalence (66.13%) of plains (0-2°) in the re-

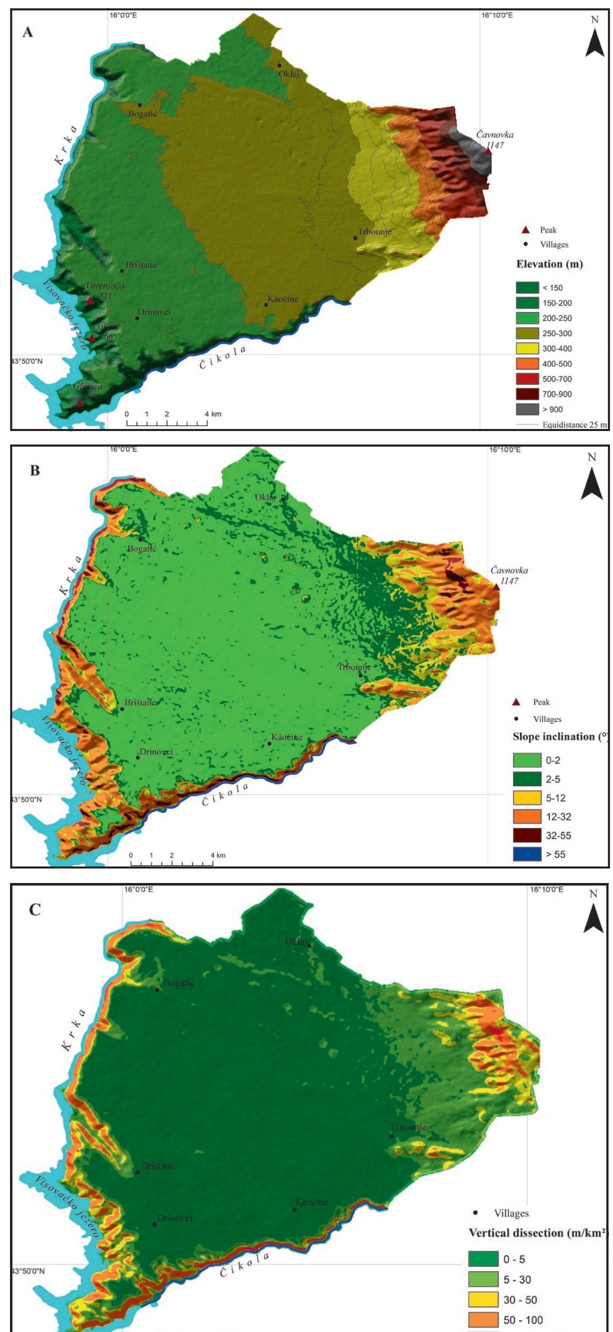

Figure 3: Elevation classes (A), slope inclination (B), and categories of relative relief (vertical dissection) (C) of the Miljevci karst plain.

searched area (Figure 3b) refer to the spreading of karst plateau. In general, the lowest slope values are related to the prevailing accumulation processes in the central part of the karst plateau. Furthermore, the significantly less represented slopes of higher slope categories (2-5°, 5-12° and 12-32°) together cover 31.9% of the area. Slightly inclined terrain (2-5°) and inclined terrain (5-12°) are covered with colluvial and diluvial material from the upper slopes, and represent a transition from the flattened central part to towards steep terrain (12-32°) of Promina mountain range and the Čikola and Krka canyons. The slopes inclined 5-12° are also present along the lateral slopes of deeper gullies and dolines where slope weathering and fluvial processes occur (intensified erosion). The slope larger than 32° occur along the steep slopes of the higher parts of the Promina mountain (700-900 m a.s.l.) and along the steepest slopes of the fluvial-derasion valley and canyon sides (42-150 m a.s.l.). Flat terrain prevails on the plateau between 200 m (28.81%) and 300 m (35.82%) a.s.l. The slopes of 2-5° and 5-12° are the most prevalent within the hypsometric class 300-400 m with a total of 6.59%, and their distribution also decreases with the increase in height. Conversely, slopes >12° are the most frequent in the lowest elevation class (< 150 m) and are related to the steep canyon sides and smaller valley extensions. The increase in height reduces their distribution and increases again from 500 meters above sea level.

Based on the range between the lowest and the highest (168.62 m/km^2) value, five categories of vertical relief dissection were determined (Figure 3c.). The average value is 10.64 m/km^2 which, according to the standard classification of vertical distribution (Lozić, 1996), places this area into poorly divided plains. Flattened terrain is the most represented category of vertical dissection. It covers 68.29% of the area, and it prevails in the 200-300 m hypsometric class. The second category (5-30 m/km^2) represents a transitional area from a centrally flatten relief to higher mountain areas and river valleys, followed by third (30-100 m/km^2) and fourth category (> 100 m/km^2), predominantly related to areas with slopes greater than 12° with more intensified slope processes. The highest classes of vertical relief dissection occupy the smallest surface of the area.

4.2. DOLINE SPATIAL DISTRIBUTION

The occurrence of the dolines was validated trough fieldwork research. Research also revealed the anthropogenic influence on the karst plateau morphology, reflected in form of underground and surface ore mines. As a result, concave depressions can be seen in the 2D view of the relief (Figure 5). Such cases should be considered when applying DEM in karst terrain analysis to avoid misperception with natural relief forms. Therefore, all validated anthropogenic depressions have been excluded from the analysis.

A total of 286 dolines were recorded in the research area of 264.89 km^2 which makes the average spatial density of only 1.1 doline/km^2. Using the Kernel

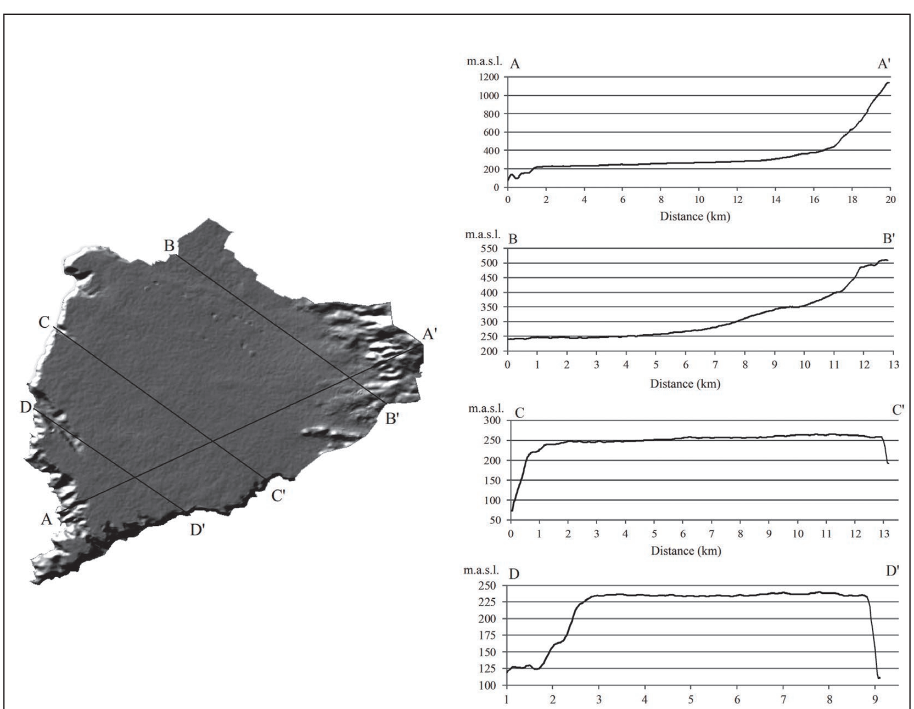

Figure 4: Morphological profiles.

Table 3: Number, proportion and density of the dolines by lithostratigraphic and chronostratigraphic units.

Lithostratigraphic unit	Chronostratigraphic unit	Total area (%)	Number	Proportion (%)	Density dolines / km²
Limestones with layers of dolomites and marls	Cenoman-Maastrichtian	**8.29**	126	**44.06**	**5.74**
Promina beds	Eocene, Oligocene	82.65	141	49.30	0.64
Foraminiferal limestones, Liburnian Formation and transitional deposits	Upper Paleocene, Lower and Middle Eocene	9.06	19	6.64	0.79

method and according to Faivre & Pahernik (2007) and Pahernik (2012) classification of doline density, six density classes were determined (Figure 6). The frequency of dolines occurrence varies from 0 to 34 dolines/km² indicating in some parts a slight density (< 10 dolines/km²), low density (10-30 dolines/km²) and medium density (30-60 dolines/km²). The occurrence of dolines is generally dispersed and heterogeneous. Two larger groups are singled out. In the east, the highest concentration of dolines (30-34.23 dolines/km²) occurs near Čikola river in the foothill of Promina Mt. (area of Gornji Gaj and Prediviště). The second core (10-30 dolines/km²) is connected to Krka river canyon around Bogatić village in the northeast. According to aforementioned classification doline density in Miljevci area

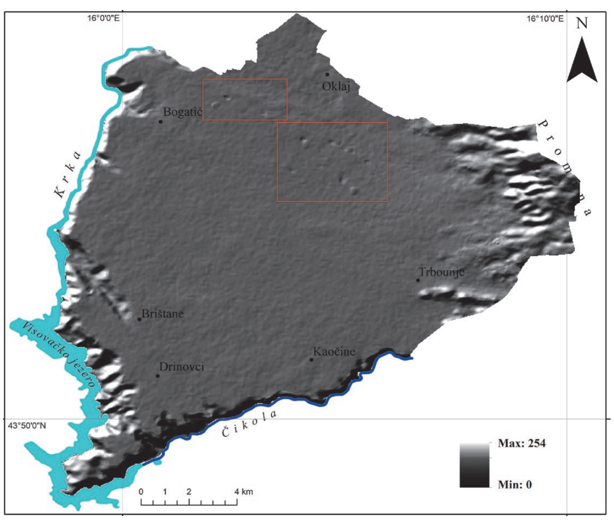

Figure 5: Concave depressions (framed by a red square) as examples of influence of bauxite mining on terrain morphology.

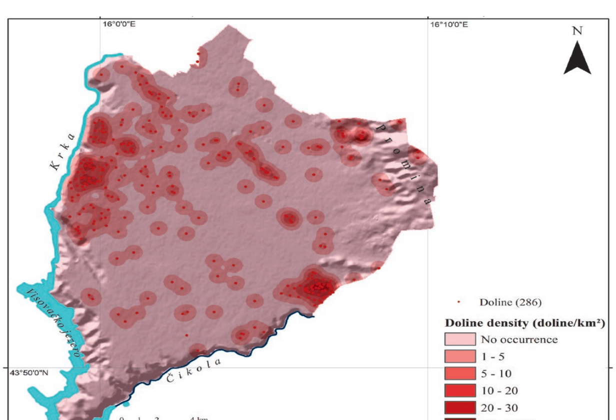

Figure 6: Doline density map.

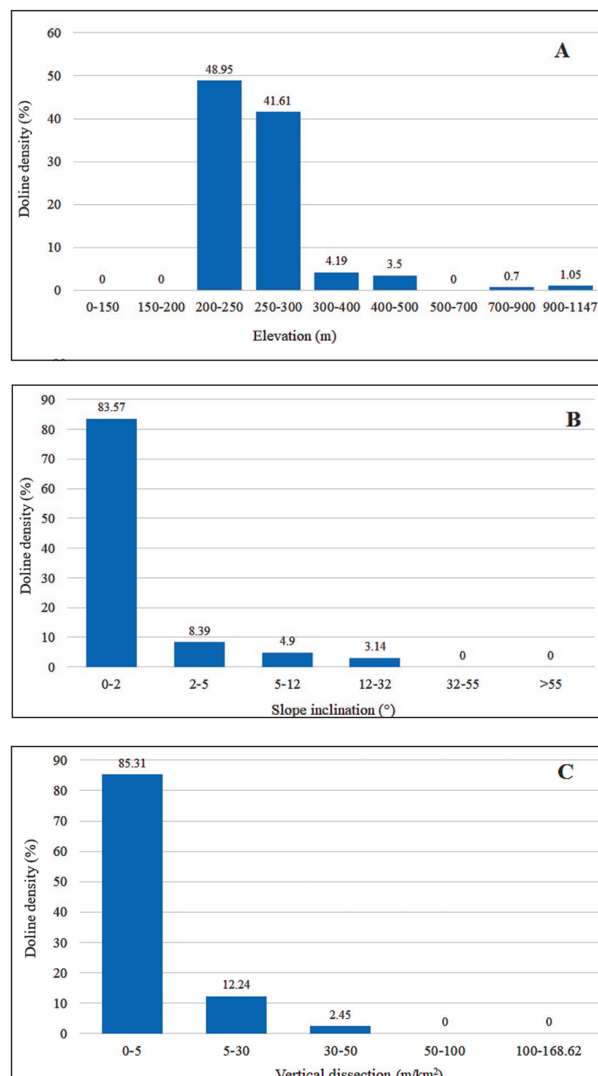

Figure 7: Statistical indicators of spatial distribution of dolines in relation to: hypsometric characteristics (A); slope (B); vertical relief dissection (C).

is low. Still, density of 30-34.23 dolines/km^2 could be considered as significant as it is in concordance with average doline density on Slunj karst plateau (42 dolines/km^2, Bočić et al., 2010) and higher than average density in mountainous regions: 27.5 dolines/km^2 in NW area of Velika Kapela (Pahernik, 2000), 19 dolines/km^2 in Northern Velebit and Senj ridge (Faivre, 1992, 1995), 18.4 dolines/km^2 in Biokovo (Bočić & Pahernik, 2011) and 10.6 dolines/km^2 in southeastern Velebit (Marković et al., 2016). Spatial distribution of dolines is important indicator of the karstification degree (Ford & Williams, 2007). Considering the doline density, and the distribution of 50 caves in similar zones (Grcić, 2019) Miljevci karst plateau is well karstified area. Also, the concentration of dolines in two zones along the river canyons (Figure 6), could indicate the existence of palaeodrainage network as proved on Una–Korana plateau (Bočić et al., 2015) thus, more likely, it poins to a relatively fast incision of the canyon and faster karstification in the zones near the main streams.

4.3. THE INFLUENCE OF GEOMORPHOMETRIC PARAMETERS AND GEOLOGICAL FEATURES ON SPATIAL DISTRIBUTION OF THE DOLINES

Overlapping the point layer of dolines through the raster substrates of the corresponding geomorphometric parameter and the lithostratigraphic characteristics resulted in the statistical representation of dolines within the classes of analysed parameters (Figure 7). Paleogene beds of Promina conglomerates, breccias, marls and bauxite are most widespread lithological unit (82.65%) encompassing 49.30% of all recorded dolines. Upper-Cretaceous limestones with intercalated dolomite and marl are least represented (8.29%). Thus, almost 45% of the dolines formed in Upper-Cretaceous limestones (Figure 9a) having the highest density (Table 3).

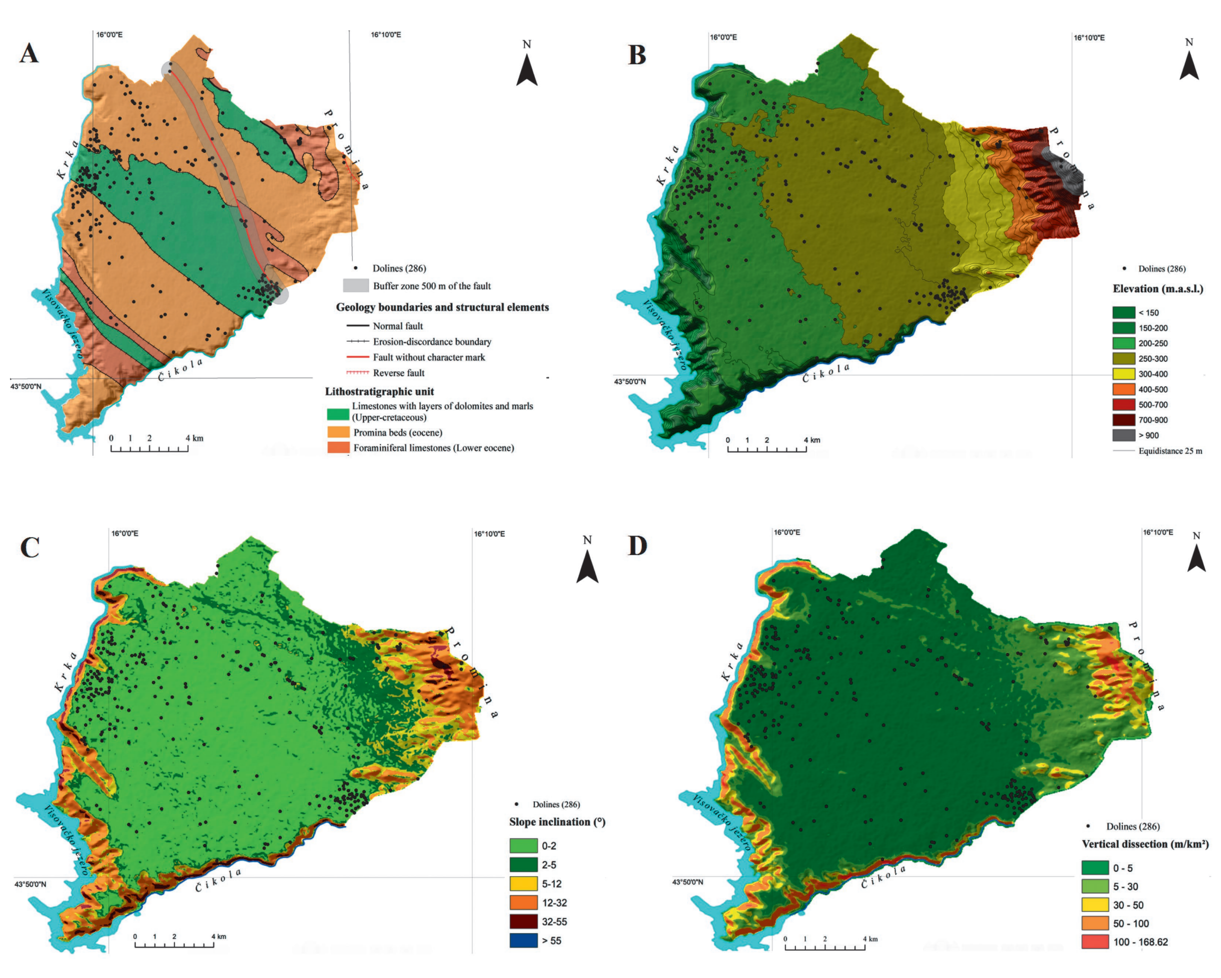

Figure 8: The relationship between the spatial distribution of the dolines and geological features (A), elevation (B), slope inclination (C) and relative relief (D). Eeach black dot represents a doline.

Apart from lithology, tectonic predisposition has a major influence on the doline occurrence and distribution (Ford & Williams, 2007). According to Faivre (1999), tectonics has a great influence on the spatial distribution of the dolines. Infiltration of surface water into crack systems along the fault zones helps doline formation. The buffer analysis revealed the occurrence of 47 dolines (16%) within 500 m of the NW-SE fault. This analysis thus indicates only a minor and localized influence of the fault on doline formation in the research area. Similar results were obtained from analogous research in SE Velebit (Marković et al., 2016) and on Slunj Plateau (Bočić et al., 2010). However, in this research only the most significant faults were considered. Minor faults and fractures which are likely to have a significant effect on the development of dolines (Faivre, 1999) are not mapped.

The density analysis shows that 90% of the dolines are distributed in prevailing altitude between 200 and 300 m a.s.l. (Figure 9b). In lower hypsometric classes (<150 m a.s.l.) no doline was recorded. We believe that such distribution is not related to elevation but to a very steep slopes along the canyons of Krka and Čikola. With elevation increase, the occurrence of dolines is drastically reduced. It can be concluded that the spatial distribution of dolines and their occurrence is not related to elevation. As proposed by Pahernik (2012) the strongest link between the doline density and geomorphometric parameters was established between slope inclination and vertical relief dissection. The number of dolines decreases with an increase of slope inclination. The highest proportion of dolines (83,57%) is developed on flat terrain (0-2°) which overlap with the elevation of 200-300 m a.s.l. (Figure 9c). Only 13% of dolines are distributed on slightly inclined terrain (2-12°). Increased distribution is observed on inclined terrain (12-32°), while at higher categories no doline development is recorded. Such distribution can be explained by a reduced corrosion on steep slopes due to rapid surface drainage. According to Pahernik (2012) low doline density on slopes with higher inclinations is attributed to shorter periods of rainfall and snowmelt water retention, as well as to the relation of higher inclination categories with active tectonic zones. The indicated relationship between slope density and slope inclination is in line with the results of a study of doline distribution in the SE Velebit area (Marković et al., 2016). Moreover, comparable results have been perceived in Slovenian Dinaric karst (Gams, 2000).

A similar trend of doline distribution is related to vertical relief dissection. 85% of all dolines were formed on flatten terrain (0-5 m/km^2) (Figure 9d). Their distribution decreases sharply with an increase in vertical dissection. Such distribution can also be explained by reduced corrosion in highly dissected areas. The vertical dissection represents a parameter that refers to the difference in elevation between various points on the surface and indicates the true extent of its evolution and current intensity morphodynamic processes (Ilie, 1970 in Artugyan & Urdea, 2016). Considering the fact that this karstic plateau is mostly flat and highest density of dolines occurs in rather narrow belts on NE and SW edges where the relief dissection is higher; we could connect the interaction of the height and slope to such occurrence, whereas higher surrounding area enables water runoff towards the plateau, thus increasing corrosion. The fact that karstification processes intensity and drainage density, in equal rainfall conditions, ratios are proportional (Ilie, 1970 in Artugyan & Urdea, 2016) and that these areas are without surface water, indicate the suitability of these areas for forming dolines. However, the influence of tectonic and lithology must be considered as well. The densest doline zones are not necessarily the most karstified areas. Research of Telbisz et al. (2009) on Biokovo Mt. and Marković et al., (2016) in south Velebit Mt. area showed that number and density of dolines is decreased in the case of predominance of larger surface area of dolines in carbonate Jelar breccias. To obtain the more relevant data on the karstification processes intensity of Miljevci karst plateau, the morphometric analysis of dolines (surface area and volume) and the identification and characterization of structural expression should be performed.

5. CONCLUSION

The results of our study demonstrates that the largest part of the research area is a well karstified plateau generally characterized by poor relief dynamics. The Krka and Čikola rivers are deeply intersected between the Miljevci and Kistanje plain. Karst plateau is best expressed in the hypsometric zone between 200 and 300 m. a. s. l. The elevation is uniform with a micro-distribution and partial disintegration of smaller hills and dolines. Most of the research area (78.3%) are slopes of 0-5°, characterized by mostly flat relief (0-30 m/km^2), indicating predominance of accumulation processes and suitability for doline development.

286 dolines were mapped within the plateau. Although the average of 1 doline/km^2 is negligible, two larger areas with density around 30 dolines/km^2 are

singled as significant and in concordance with average doline density in Croatia. Since the density of sinkholes is quite low in contrast to well-developed karst; further studies of doline density should include a morphodynamic perspective. We confirmed that flat areas of karstic plateaus, without active drainage, make favorable topographic conditions for doline formation. 85% of their occurrence is related to plains (0-2°) and a flatten terrain (0-5 m/km^2), mostly in the foothill of the more dissected area. Generally, the number of dolines decreases with an increased inclination. Furthermore, almost 45% of the dolines formed in least represented lithological unit (Upper-Cretaceous limestone) confirming the high interdependence between the lithology and doline density.

It is evident that the surface drainage coefficient has been reduced on Miljevci Plateau, which increases water infiltration and related corrosion along infiltration flowpaths and contributes to greater karstification represented in doline distribution. Their distribution in two zones along the river canyons could indicate the existence of palaeodrainage. Further investigations should be extended to the area of the entire North-Dalmatian plateau, with special attention being paid to field research and determination of the impact of structural elements on their spatial distribution as well as the morphometric characteristics of the dolines. Besides, more studies should be done on the karst genesis in terms of morphology or morphometry compared to topographic or structural features.

ACKNOWLEDGMENTS

Authors would like to thank to Fran. Domazetović for the assistance in processing spatial data analyses, Blaž Miklavič for constructive suggestions and language editing, and anonymous reviewers whose inputs have improved the overall quality of this paper.

REFERENCES

Artugyan, L., Urdea, P., 2016. Using Digital Elevation Model DEM in karst terrain analysis. Study case : Anina mining area Banat Mountains Romania. Carpathian Journal of Earth and Environmental Sciences, 111(1): 55 – 64.

Ballut, C., Faivre, S., 2012. New data on the dolines of Velebit Mountain: An evaluation of their sedimentary archive potential in the reconstruction of landscape evolution. Acta Carstologica, 41(1): 59-74. http://dx.doi.org/10.3986/ac.v41i1.48

Bočić, N., Pahernik, M., Bognar, A., 2010. Geomorfološka obilježja Slunjske zaravni. Hrvatski geografski glasnik, 72(2): 5-26. https://doi.org/10.21861/hgg.2010.72.02.01

Bočić, N., Pahernik, M., 2011. Ponikve Parka prirode Biokovo – prostorna analiza. In: Protrka, K. Škrabić, H., Srzić. (Eds.), Znanstvenostručni skup *„Biokovo na razmeđi milenija: razvoj parka prirode u 21. stoljeću“ Knjiga sažetaka*, Javna ustanova „Park prirode Biokovo“, Makarska, 17-19 November.2011., pp. 68.

Bočić, N., Pahernik, M., Mihevc, A., 2015. Geomorphological significance of the palaeodrainage network on a karst plateau: The Una–Korana plateau, Dinaric karst, Croatia. Geomorphology, 247: 55–65. https://doi.org/10.1016/j.geomorph.2015.01.028

Bognar, A., 2001. Geomorfološka regionalizacija Hrvatske. Acta Geographica Croatica,
34: 7-29.

Bognar, A., Faivre, S., Buzjak, S., Pahernik, M., Bočić, N., 2012. Recent landform evolution in the Dinaric and Pannonian Region of Croatia, In: Lóczy, D., Stankoviansky, M., Kotarba, A., (Eds.), *Recent Landform Evolution*. Springer, Heidelberg-London-New York, pp. 313-344.

Buzjak, N., Buzjak, S., Orešić, D., 2011. Florističke, mikroklimatske i geomorfološke značajke ponikve Japage na Žumberku. Šumarski list, 1–2: 127-137.

Buzjak, N., Petković, A., Faivre, S., 2013. Intenzitet prirasta i supkutane krške korozije u dolini rijeke Krke Hrvatska. Hrvatski geografski glasnik, 75(2): 59-79.

Croatian Meteorological and Hydrological Service (CMHS), 2021. Average monthly and annual air temperature °C and mean monthly and annual precipitation mm for the Šibenik and Drniš station, for the 1991 - 2020 period.

Daura, J., Sanz, M., Fornos, J.J., Asensio, A., Julia, R., 2014. Karst evolution of the Garraf Massif (Barcelona, Spain): doline formation,chronology and archaeo-palaeontological archives. Journal of Cave and Karst Studies, 76(2): 69–87. http://dx.doi.org/10.4311/2011ES0254

EU-DEM, 2018: Digital Elevation Model over Europe. https://data.eox.at/eudem/[Accessed 6 February 2018].

Faivre, S., 1992. Analize gustoće ponikava na Sjevernom Velebitu i Senjskom bilu. Senjski zbornik, 19: 13-24.

Faivre, S., 1994. Strukturno-geomorfološka analiza tipova dolinske mreže Sjevernog Velebita i Senjskog bila. Senjski zbornik, 21: 9-24.

Faivre, S., 1995. Neke temeljne strukturno-geomorfološke značajke sjevernog Velebita i Senjskog bila, In: Pepeonik, Z. (Ed.), Zbornik radova 1. Hrvatskog geografskog kongresa, Hrvatsko geografsko društvo, Zagreb, pp. 156-169.

Faivre, S., 1999. Landforms and tectonics of the Velebit mountain range (Outer Dinarides, Croatia), Doktorska disertacija, Sveučilište u Zagrebu, Prirodoslovno-matematički fakultet, Geografski odsjek, Zagreb, Croatia, pp. 360.

Faivre, S., Bocquet, J., 1999. Variation spatiale des contraintes tectoniques calculées a partir des dolines; Montagne de Velebit, Croatie. Etudes de géographie physique. CAGEP, 28: 83-88

Faivre, S., Reiffsteck, P., 1999. Spatial distribution of dolines as an indicator of recent deformations on the Velebit mountain range. Geomorphologie: Relief, Processus, Environment, 2: 129-142.

Faivre, S., Reiffsteck, P., 2002. From doline distribution to tectonic movements. Example of the Velebit mountain range, Croatia. Acta carsologica, 31(3): 139-154. http://dx.doi.org/10.3986/ac.v31i3.384

Faivre, S., Pahernik, M., 2007. Structural influences on the spatial distribution of dolines, Island of Brač, Croatia. Zeitschrift für Geomorphologie, 51(4):487–503. https://doi.org/10.1127/0372-8854/2007/0051-0487

Filipčić, A., 2000. Razgraničenje Köppenovih klimatskih tipova Cf i Cs u Hrvatskoj. Acta Geographica Croatica, 35: 7-18.

Ford, D., Williams, P., 2007. Karst Hydrogeology and Geomorphology. John Wiley and Sons Ltd, Chichester, 562.

Friganović, M., 1961. Polja gornje Krke. Acta Geographica Croatica, 3(1). 8-164.

Gabrovšek, F., Stepišnik, U., 2011. On the formation of collapse dolines: A modelling perspective. Geomorphology, 134: 23-31. https://doi.org/10.1016/j.geomorph.2011.06.007

Gallay, M., Kaňuk, J., Hofierka, J., Hochmuth, Z., Meneely, J., 2015. Mapping and geomorphometric analysis of 3-D cave surfaces: a case study of the Domica Cave, SlovakiaE In: Jasiewicz, J., Zwoliński, Z., Mitasova, H., Hengl, T. (Eds.), Geomorphometry for Geosciences. Bogucki Wydawnictwo Naukowe, Adam Mickiewicz University in Poznań - Institute of Geoecology and Geoinformation, Poznań, Poland, pp. 69–73.

Gams, I., 2000. Doline Morphogenetic Processes from Global and Local Viewpoints. Acta Carsologica, 29(2): 123-138. https://doi.org/10.3986/ac.v29i2.453

Grimani, I., Juriša, M., Šikić, A. K., Šimunić A., 1966-1975. Tumač za osnovnu geološku kartu 1 : 100 000 list Knin L 33-141, Savezni geol. Zavod [Map].

Grcić, I., 2019. Geomorfološke značajke miljevačkog dijela Sjevernodalmatinske krške zaravni (Geomorphological characteristics of the Miljevci plateau in the area of the Notrh Dalmatian karst plateau) [Master thesis]. University of Zadar, 72.

Hofierka, J., Gallay, M., Kaňuk, J., Šašak, J., 2017. Modelling Karst Landscape with Massive Airborne and Terrestrial Laser Scanning Data. Springer, Cham, pp. 141–154. https://doi.org/10.1007/978-3-319-45123-7_11

Ilie, I., 1970. Karst Geomorphology. Centrul de multiplicare al Univ. Bucureşti, 348 pp.Ivanović, A., Sikirica, V., Marković, S., Sakač, K., 1977. Osnovna geološka karta 1:100 000 list Drniš, Institut za geološka istraživanja, Zagreb [Map].

Kruk, B., Dedić, Ž., Kovačević-Galović, E., Kruk, L., 2014. Osnove gospodarenja mineralnim sirovinama na području općine Promina u Šibensko-kninskoj županiji, Hrvatski geološki institut – Zavod za mineralne sirovine, Zagreb, 38 pp.

Lozić, S., 1996. Nagibi padina kopnenog dijela Republike Hrvatske. Acta Geographica Croatica, 31: 41-50.

Mamužić, P., 1971. Osnovna geološka karta 1:100 000 list Šibenik, Institut za geološka istraživanja, Zagreb [Map].

Marković, J., Bočić, N., Pahernik, M., 2016. Prostorni raspored i gustoća ponikava jugoistočnog Velebita. Geoadria 21(1), 1-28.

Meng, X., Xiong, L., Yang, X., Yang, B., Tang, G., 2018. A terrain openness index for the extraction of karst Fenglin and Fengcong landform units from DEMs. Journal of Mountain Science15, 752–764. https://doi.org/10.1007/s11629-017-4742-z

Mihevc, A., 2007: The Age of Karst Relief in West Slovenia. Acta Carsologica, 36(1):35-44. https://doi.org/10.3986/ac.v36i1.206

Mihevc, A., Mihevc, R., 2021: Morphological characteristics and distribution of dolines in Slovenia, a study of a lidar-based doline map of Slovenia. Acta Carsologica, 50(1): 11-36. https://doi.org/10.3986/ac.v50i1.9462

Mihljević, D., 1994. Analysis of spatial characteristics in distribution of sink-holes, as an geomorphological indicator of recent deformations of geological structures. Acta Geographica Croatica, 29: 29–36.

Moreno-Gómez, M., Liedl, R., Stefan, C., Moreno-Gómez, M., Liedl, R., Stefan, C., 2019. A New GIS-Based Model for Karst Dolines Mapping Using LiDAR; Application of a Multidepth Threshold Approach in the Yucatan Karst, Mexico. Remote Sensing, 11: 1147. https://doi.org/10.3390/rs11101147

Öztürk, M.Z., Şener, M.F., Şener, M., Şimşek, M., 2018. Structural controls on distribution of dolines on Mount Anamas Taurus Mountains, Turkey. Geomorphology, 317: 107–116. https://doi.org/https://doi.org/10.1016/j.geomorph.2018.05.023

Pahernik, M., 2000. Prostorni raspored i gustoća ponikava SZ dijela Velike Kapele – rezultati računalne analize susjedstva. Geoadria, 5: 105-120.

Pahernik, M., 2012. Spatial density of dolines in the Croatian Territory. Hrvatski geografski glasnik, 74(2): 5-26.

Pardo-igúzquiza, E., Pulido-Bosch, A., López-Chicano, M., Durán, J.J., 2016. Morphometric analysis of karst depressions on a mediterranean karst massif, Geografiska Annaler: Series A, Physical Geography, 98(3): 247-263. https://doi.org/10.1111/geoa.12135

Perica, D., Orešić, D., Trajbar, S., 2005. Geomorfološka obilježja doline i porječja rijeke Krke s osvrtom na dio od Knina do Bilušića Buka. Geoadria, 10(2): 131-156.

Pike, R.J., Evans, I.S., Hengl., T., 2009. Chapter 1 geomorphometry: a brief guide. In: Hengl, T., Reuter, H.I. (Eds.), Developments in Soil Science, Geomorphometry. Elsevier, Amsterdam, pp. 3-30. https://doi.org/10.1016/S0166-2481(08)00001-9

Plan, L., Decker, K., 2006. Quantitative karst morphology of the Hochschwab plateau, Eastern Alps, Austria. Zeitschrift für Geomorphologie Supplementband, 147: 29–54.

Polšak, A., Korolija, B., Fritz, F., Božičević, S., 1990. Geološka i hidrogeološka obilježja Nacionalnog parka "Krka", Ekološke monografije, knjiga 2, Zbornik radova sa Simpozija: "NP Krka – stanje i problemi zaštite ekosistema, HED, Zagreb, pp. 15-50.

Roglić, J., 1957. Zaravni na vapnencima. Geografski glasnik, 19: 109-133

Sauro, U., 2013. Landforms of mountainous karst in the middle latitudes: reflections, trends and research problems. Acta Carsologica 42(1): 5–16. https://doi.org/10.3986/ac.v42i1.629

Sauro, U., 2003. Dolines and sinkholes: Aspects of evolution and problems of classification. Acta Carsologica, 32, 41–52. https://doi.org/10.3986/ac.v32i2.335

Sauro, U., Francese R., Ferrarese F., Miola A., Mozzi P., Rondo, G.Q., Trombino, L., Valentini, G., 2009. Doline Fills - Case Study of the Faverghera Plateau Venetian Pre-Alps, Italy. Acta Carsologica 38(1): 51-63. https://doi.org/10.3986/ac.v38i1.136

Siart, C., Forbriger, M., Nowaczinski, E., Hecht, S., Höfle, B., 2013. Fusion of multi-resolution surface terrestrial laser scanning and subsurface geodata ERT, SRT for karst landform investigation and geomorphometric quantification. Earth Surfface Processes and Landforms, 38: 1135–1147. https://doi.org/10.1002/esp.3394

Silva, O.L., Bezerra, F.H.R., Maia, R.P., Cazarin, C.L., 2017. Karst landforms revealed at various scales using LiDAR and UAV in semi-arid Brazil: Consideration on karstification processes and methodological constraints. Geomorphology, 295: 611–630. https://doi.org/10.1016/J.GEOMORPH.2017.07.025

Šiljeg, A., 2013. Digitalni model reljefa u analizi geomorfometrijskih parametara – Primjer PP Vransko jezero. [PhD thessis]. Geografski odsjek PMF-a, Sveučilište u Zagrebu, 198.

Šušteršič, F., 2016. Are "Collapse Dolines" Formed Only by Collapse?. Acta Carsologica, 29(2): 213-230. https://doi.org/10.3986/ac.v29i2.461

Tagil., S., Jenness. J, 2008. GIS-Based Automated Landform Classification and Topographic, Landcover and Geologic Attributes of Landforms Around the Yazoren Polje, Turkey. Journal of Applied Sciences, 8: 910-921. https://dx.doi.org/10.3923/jas.2008.910.921

Telbisz, T., Mari, L., Ćalić, J., 2007. Doline morphometry of Mt.Miroč using GIS methods. Bulletin of the Serbian Geographical Society, 87(2): 21-30.

Telbisz, T., Dragušica, H., Nagy, B., 2009. Doline Morphometric Analysis and Karst Morphology of Biokovo Mt Croatia Based on Field Observations and Digital Terrain Analysis. Hrvatski Geografski Glasnik, 71(2): 5 – 22.

Telbisz, T., Mari, L., Szabó, L., 2011. Geomorphological Characteristics of the Italian Side of Canin Massif Julian Alps Using Digital Terrain Analysis and Field Observations. Acta Carsologica, 40(2): 255–266. http://dx.doi.org/10.3986/ac.v40i2.10

Tîrlă, L., Drăguşin, V., Bajo, P., Covaliov, S., Cruceru, N., Ersek, V., Hanganu, D., Hellstrom, J., Hoffmann, D., Mirea, I., Sava, T., Sava, G., Şandric, I., 2020. Quaternary environmental evolution in the South Carpathians reconstructed from glaciokarst geomorphology and sedimentary archives. Geomorphology, 354: 107038. https://doi.org/https://doi.org/10.1016/j.geomorph.2020.107038

Velić, I., Vlahović, I., 2009. Tumač geološke karte 1:300.000. Hrvatski geološki institut, Zagreb [Map].