Characterization of Valleys and Gullies of the North and Central Velebit Coastal Slope

Klara Grošanić[1,], Marin Mićunović[1], Sanja Faivre[1]*

[1] University of Zagreb, Faculty of Science, Department of Geography, Marulićev trg 19/II, Zagreb, Croatia, klara.grosanic@student.geog.pmf.hr, mmicunov@geog.pmf.hr, sfaivre@geog.pmf.hr

* corresponding author

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Abstract: Climate change is an important issue today, affecting many geomorphological processes in different environments. Increased frequency of precipitation extremes results in frequent flooding and gullying. Consequently, short and intense rainfalls cause the activation of torrential flows, activating numerous dry valleys and gullies. The coastal slope of Velebit Mountain hosts deep valleys and gullies of various dimensions from a few meters to thousands of meters in length. In this research, a morphometric analysis of selected valleys and gullies and their drainage basins in the area of North and Central Velebit was conducted in GIS using a digital elevation model, topographic maps and satellite imagery. 114 valleys and gullies and their corresponding drainage basins were identified, with an average length of 1.2 km and average basin area of 2.6 km^2. Strong correlations were found between the area of drainage basins and 1) the lengths of the gullies and 2) the Strahler stream order of the main channel. Lateral profiles showed possible differences in erosion activity. The obtained results contribute to the existing knowledge about the morphology of valleys and gullies on the Velebit coastal slope, but also encourage further research using GIS and remote sensing.

Keywords: geomorphology, gullies, gully erosion, GIS, Velebit.

1 Introduction

Definitions of gullies are often inconsistent due to the various forms they take worldwide (Thwaites et al. 2021). Generally, gullies are described as elongated landforms formed by intermittent flows activated by intense rainfall, ranging up to several hundred meters in length, tens of meters in width, and depths of 20 to 30 meters, sometimes making them difficult to differentiate from (dry) valleys. Gully depths exceed their width, and their cross-sections take the shape of the letter V (Goudie 2004). It is important to emphasize the hydrological aspect of their formation: by torrential flows due to intense rainfall that rapidly transport eroded material, often causing significant damage to surrounding land and infrastructure (Castillo and Gómez 2016, Jahić 2017). This is why interest in researching gullies and gully erosion has increased since the beginning of the 21st century, especially in the Mediterranean region (Castillo and Gómez 2016, Domazetović et al. 2019).

Velebit Mountain is part of the External Dinarides with a total length of 145 km. According to Bognar's (2001) geomorphological regionalisation of Croatia, Velebit belongs to the meso-geomorphological region 2.1.7. Velebit Mountain ridge-massif. In this analysis, the Northern and Central Velebit coastal slope was assessed. Northern Velebit extends from Oltari to Veliki Alan pass, while Central Velebit continues south to the Oštarije pass. In this study, the eastern boundary of the research area was defined by the boundaries of gully and valley drainage basins (Figure 1). The coastal slope consists predominantly of carbonate deposits from Mesozoic (at higher altitudes) and Cenozoic eras (at lower altitudes) (Mamužić and Milan 1966, Nikler et al. 1967, Mamužić et al. 1969, Sokač et al. 1970, Sokač et al. 1974). Due to the carbonate composition, the coastal slope is characterized by karst relief forms and the absence of permanent surface drainage (Rogić 1958). The area belongs to the humid subtropical climate type Cfa (Filipčić 1998), with an average annual temperature of 15.6 °C and an average annual precipitation of 1285 mm (DHMZ 2023). Most of the precipitation falls during the colder half of the year, however, short and intense rainfall is common during the summer months (Šegota and Filipčić 1996, Perica and Orešić 1999).

The aim of this research is to present the basic morphometric characteristics of gullies, valleys and their

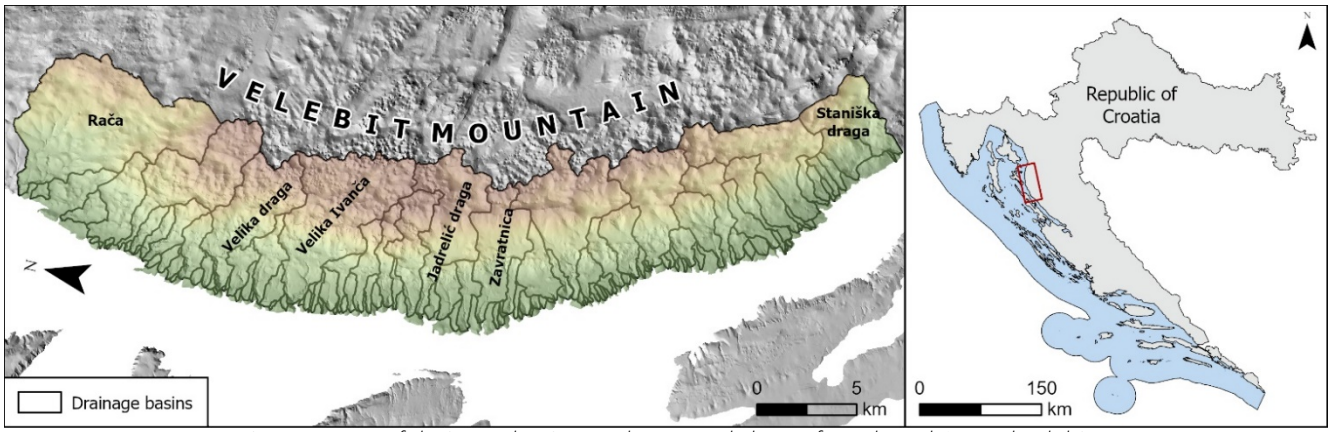

Figure 1. Map of drainage basins on the coastal slope of North and Central Velebit.

drainage basins on the coastal slope of North and Central Velebit with the help of remote sensing and GIS methods. Obtained results will contribute to the existing knowledge about gullies and valleys in this area and serve as a base for further studies on their formation.

2 Materials and methods

Gully, valley and drainage basin data was derived from a digital elevation model (DEM) of the Republic of Croatia with a pixel size of 5x5m (DGU 2019), using the Hydrology toolset in the Spatial Analyst extension of ArcGIS Pro. The morphometric analysis of the drainage basins was conducted using the Slope, Aspect and Focal statistics functions. Gully and valley thalwegs were extracted using the functions Fill, Flow direction and Flow accumulation. The values of the resulting raster were reclassified into two classes using the Set Null function with a threshold value of 1000, thereby isolating pixels indicating relevant flow paths. Gully and valley extents were then mapped by tracing the acquired thalwegs. High-resolution satellite imagery (Maxar technologies, CNES/Airbus), orthophoto provided by State Geodetic Administration (2021) and extents of intermittent streams in the Croatian base map 1:5000 (DGU n.d.) were utilized to verify the results obtained in ArcGIS Pro software. The Stream Order function was used to classify the streams using the Strahler method. Drainage basins were delineated using the Basin function in the Hydrology toolset. The areas of the drainage basins and lengths of mapped gullies and valleys were calculated in ArcGIS Pro. For easier visualization, relief shading was generated using the Hillshade function. Longitudinal and lateral profiles of six selected gullies and valleys were obtained using the Profile function.

3 Results

3.1 Drainage basin properties

The slope values of extracted drainage basins were classified into 6 categories. The most common slope category throughout is 12°–32° (steep terrain), accounting for 67.3% of the area. Additionally, two parallel segments of lower slope values, 0°–12°, can be highlighted at altitudes of 100–300 and 600–900 meters above sea level. Western slope orientation dominates throughout the studied area. The relief energy of the studied area mostly falls into two categories according to Bognar (1992): 100 – 300 m/km^2 (55.9%) and > 300 m/km^2 (36.9%). 114 drainage basins of gullies and valleys were identified, their sizes varying from 0.03 km^2 to 41.76 km^2, while the average basin size is 2.62 km^2. Based on the digital elevation model, thalwegs were derived, and their streams classified using the Strahler stream order. The Pearson's correlation coefficient of 0.69 was calculated between the basin area and the highest Strahler order of their thalwegs, which present a moderately strong correlation (Šošić and Serdar 2002).

3.2 Gully and valley properties

The average length of gullies and valleys is 1200 m, with the shortest gully being 61 m and the largest 17,068 m long. The Pearson's correlation coefficient between the basin area and the length of the corresponding gullies and valleys equals 0.82, indicating a strong correlation. A total of 96 simple gullies (without tributaries) and 18 complex valleys (with 1 or more tributaries) were identified. Complex valleys coincide with the largest drainage basins extending to the very top of the coastal slope and the main ridge. Simple gullies extend perpendicular to the direction of the slope and are prevalent in Central Velebit, while greater complexity and density of gullies and valleys is visible in Northern Velebit. The 86 % of simple gullies initiate under 300 m above sea level while the heads of the longest ones are generally not found above 1000 m above sea level. A gully density of 0.35 gullies/km^2 was determined in the researched area.

The longitudinal profiles of Rača, Zavratnica, and Staniška Draga gullies are mostly uniform, with no significant changes in slope along the course, while Velika Ivanča clearly exhibits two pronounced segments of lower inclination. Upper reaches are generally characterized by steeper slopes. Lateral profiles of the lower reaches of are mostly symmetrical. Widths of the gullies and valleys range from 150 m to 500 m. The bottoms of gullies Rača, Velika Ivanča, Jadrelić Draga, and Zavratnica are more rounded, and their profiles take on a U shape. A different shape of the lateral profile, transitioning from U to V, is observed in Velika Draga and Staniška Draga. The profiles reveal that the incisions vary from 35 m to 200 m. Lateral profiles of the upper reaches are more uneven compared to the lower reaches where greater differences in shapes can be observed. Here, on the upper reaches gullies and valleys widths range from 55 m (Zavratnica) to 300 m (Rača) and incisions range from 5 m at Staniška Draga to 50 m at Rača. As expected, it is evident that widths and depths of gullies and valleys of the upper reaches are smaller compared to those of the lower reaches.

4 Discussion

Processes that shape gullies are influenced by hydrological and climatic conditions, as well as lithology (Thwaites et al. 2021). Larger forms like valleys are also influenced by structural properties of the area (Ballut and Faivre 2012). Slope is a major factor in activation of gullies and valleys and sediment transport by flash floods, as well as the erosive power of the flow (Faivre et al. 2011, Ružić et al. 2011). Steep slopes increase surface runoff but also reduce infiltration on carbonate substrates enabling incision. Morphometric analysis of the studied area revealed the prevalence of slopes ranging from 12° to 32°, which, according to previous studies, favors the formation of gullies. Consequently, denudation processes become stronger on slopes above 12°, leading to increased intensity of linear erosion (Lončar 2009, Faivre et al. 2011). Two elongated areas of gentler slopes (0°–12°) have been detected in the analysis, which, according to Bognar (1994), correspond to the upper pediment (formed from Eocene to Miocene) and the lower pediment (formed from Pliocene to Pleistocene). Further downstream, and towards the coast, the incisions deepen, forming deep gullies, as revealed by the analysis of selected lateral

profiles. Climate characteristics of a region have a significant impact on erosion intensity (Goudie 2004). In the studied area, the lowest amount of precipitation occurs in summer, while the maximum occurs in autumn, mainly in the form of short and intense showers that trigger flash floods and initiate gully formation (Perica and Orešić 1999) which has also been recorded on the nearby island of Krk (Faivre et al. 2011).

The heads of the identified gullies and valleys are located within the inclination class of 12°–32° and at elevations of up to 1000 meters, where the incision into the substrate begins due to the formation of torrential flows. The longitudinal profiles are characterized by relatively uniform slopes, but some deviations have been identified. Larger, steep declines within certain gullies can be attributed to anthropogenic elements, especially roads, and thus influence erosion intensity and sediment transport. Deviation from the equilibrium state may indicate incision or tectonic activity after the main phase of formation (Benac 1992). More pronounced differences have been observed in the lateral profiles, where the presence of U and gentle V shapes is visible. According to Goudie (2004) and Kirkby and Bracken (2009), after the incision process, slope processes dominate on steep gully sides, causing the filling of the gully bed and consequently smoothing the slopes within, taking on rounded shapes. The cause of differences in the shape of the gully and valley profiles may be also the difference in activity (those with V profiles are still actively incising into the slope, while those with a U shape are dominated by slope processes).

The formation and evolution of gullies and valleys in this area must be contextualized within the Pleistocene glaciation and the Holocene sea-level rise. The existence of glaciers during the Last Glacial Maximum in North and Central Velebit has been proven, parts of which expanded into the area of the coastal slope (Faivre and Bognar 2006). The melting of glaciers formed powerful flows that drained towards the bottom of the then dry Velebit Channel and formed deeply incised gullies and valleys (Faivre et al. 2019). With the rise in sea level in the Holocene (Surić et al. 2009), the bottoms of the formed gullies and valleys were submerged, forming coves (Faivre and Mićunović 2017). Erosional base level changes result in reduction of the intensity of incision, and the gullies are gradually filled with loose material, with the occurrence of repeated flash flood activation during periods of intense rainfall (Benac 1992, Faivre et al. 2011).

5 Conclusions

On the coastal slope of Northern and Central Velebit, an analysis of the digital elevation model, topographic maps and remote sensing data revealed 114 gullies and valleys with an average length of 1.2 km and corresponding drainage basins with an average area of 2.62 km^2. Strong correlations were found between the area of drainage basins and 1) the lengths of the gullies and 2) the Strahler stream order of the main channel. Additionally, an analysis of longitudinal and lateral profiles of six selected gullies and valleys was conducted.

The formation of gullies and valleys in the studied area is conditioned by geological, geomorphological, hydrological, vegetational and climate characteristics of the region, with the greatest role played by high slope values (12°–32°) and climate with simultaneous occurrences of seasonal intense rainfall. We assume that the main incision phase occurred during the Last Glacial Maximum, enhanced by periodical melting of the Velebit mountain glaciers when water flowed towards the then-existing erosional base level, forming deep gullies and valleys. Subsequent sea level rise in the Holocene submerged the mouths of gullies and valleys, forming deep bays, after which the incision process slowed down. Predominantly U-shaped lateral profiles confirm this thesis, indicating denudation processes on the slopes and the relative age of the analyzed gullies and valleys. However, there are differences in the profile shapes, suggesting differences in their age and activity. The obtained results contribute to the existing knowledge about the morphology of valleys and gullies on the Velebit coastal slope, but also encourage further research with the help of GIS and remote sensing. GIS and remote sensing proved particularly useful in this research as the Velebit coastal slope covers a large, sometimes hardly accessible area. Satellite imagery and topographic maps revealed to be useful in all phases of this research and especially in the verification of the obtained results.

6 Data

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