Objekt ovoga istraživanja su padine uzvišenja širega područja Duvanjskog polja. Padine se mogu definirati kao reljefne plohe određene geografskim položajem, nagibom u odnosu na horizontalnu površinu, izloženosti (ekspozicijom) u odnosu na strane svijeta, te stupnjem zakrivljenosti (profilne i planarne). Recentni oblik padina posljedica je utjecaja niza prirodnih i društvenih faktora tijekom geneze i evolucije reljefa. Analizom morfometrijskih parametara moguće je dovesti u vezu značajke padina s geološkom građom i sastavom, ali i ostalim prirodnog-geografskim čimbenicima (npr. klima, pedologija, vegetacija itd.).

Ciljevi ovoga istraživanja su: a) analiza morfometrijskih pokazatelja reljefa, b) analiza odnosa između morfometrijskih pokazatelja, strukturnih i litoloških značajki i c) sinteza svih analiziranih pokazatelja da bi se dobio detaljniji uvid u egzogeomorfološke i morfostrukturne značajke područja i omogućila procjenu opsega i intenziteta dominantnih geomorfoloških procesa. Pri tome, posebna pažnja posvećena je detaljnoj geomorfometrijskoj analizi makromorfostrukture šire područja Duvanjskog polja u okružju GIS-a na temelju digitalnog modela reljefa (DMR). Geomorfometrijska analiza reljefa primijenjena u ovom radu uključila je korištenje različitih metoda za precizno računanje numeričkih parametara reljefa istraživanog područja, što je omogućilo međusobnu usporedbu navedenih parametara, ali i usporedbu s kartom tektonskih jedinica i geološkom kartom. Cilj ovakvog pristupa je egzaktnija interpretacija morfometrijskih parametara reljefa kao indikatora značajki endogenih i egzogenih procesa na istraživanom području.

Ključne riječi: geomorfometrijska analiza, morfometrijski parametri, padine, šire područje Duvanjskog polja

The objects of this study are the hillslopes in the broader area of Duvanjsko polje (Bosnia and Herzegovina). Slopes can be defined as relief surfaces determined by geographical position, slope inclination (related with horizontal surface), aspect, and degree of curvature (profile and planar). Recent slope shapes can be defined as results of series of natural and anthropogenic factors during relief genesis and evolution. It is possible to correlate slope characteristics with geological structure and other natural geographic features (climate, soils, vegetation etc.) using geomorphometrical analysis.

The main aims of this study are: a) analysis of morphometric relief indicators, b) analysis of relationships between morphometric indicators, structural and lithological features, and c) synthesis of all analyzed indicators in order to better understand exogeomorphological and morphostructural features of the investigated area. The final intention is to assess the extent and intensity of the dominant geomorphologic processes. Special attention was given to the detailed geomorphometrical analysis of morphostructures in the broader area of Duvanjsko polje in GIS environment based on DMR. The applied geomorphometrical relief analysis included the use of different methods for precise calculation of the investigated area's numerical relief parameters, which enabled a mutual comparison of specified parameters and comparison with tectonic units and lithology maps. The aim of this approach is a more exact analysis and interpretation of morphometric relief parameters as indicators of the investigated area's endogenous and exogenous processes' characteristics.

Key Words: geomorphometrical analysis, morphometric parameters, hillslopes, broader area of Duvanjsko polje
Uvod

U ovom radu provedena je geomorfometrijska analiza temeljnih parametara reljefa šireg područja Duvanjskog polja (nagiba, ekspozicija, profline i planarne zakrivljenosti) i njihova značajka kao indikatora endogenih i egzogenih geomorfoloških procesa. Analiza je u najvećoj mjeri usmjerena na padine nagiba > 2° na području širega planinskog okvira Duvanjskog polja. Dan je i osvrt na površine koji pripadaju kategoriji < 2°, što se prije svega odnosi na područje samog polja, ali i na ostale manje reljefne oblike s ovom kategorijom nagiba izvan Duvanjskog polja.

Geomorfometrija je znanost o kvantitativnim obilježjima Zemljine površine (Pike i dr., 2009.). Ona predstavlja analitičko-kartografski pristup u proučavanju topografskih obilježja Zemlje kao i interdisciplinarno područje proizašlo većinom iz matematike, prirodnih znanosti i informatike. S obzirom na objekt geomorfometrije, proučavanjem manjih reljefnih oblika bavi se specifična, dok se reljefom kao cjelinom bavi opća geomorfometrija. Opća geomorfometrija osnova je za kvantitativnu usporedbu većih reljefnih oblika, a uključuje metode koje u osnovi nisu geomorfološke (MacMillan, Shary, 2009.). U ovom radu primijenjena su načela i metode opće geomorfometrije, koja se odnosi na računalnu analizu GIS-a šireg područja Duvanjskog polja u promatranim granicama.

Suvremena geomorfometrijska analiza, temeljena na metodama GIS-a, odnosi se u prvom redu na analizu digitalnog modela reljefa (Franklin, 1987.; Jordan, Csillag, 2001.; Ganas et al., 2005.; Smith, Clark, 2005.). Digitalni model reljefa matematički je prikaz Zemljine površine u rasterskom ili vektorskom obliku koji sadrži nizove vrijednosti visina. S obzirom na prostornu rezoluciju postoje različiti rasterski modeli reljefa, a o njoj izravno ovisi kvaliteta i preciznost izlaznih rezultata. Za potrebe ovoga rada izrađen je rasterski digitalni model reljefa Duvanjskog polja i rubnih padina uzvišenja koja ga okružuju automatskom vektorizacijom izohipsa s topografskih karata mjerila 1:25 000.

Geomorfometrijski parametri mogu se izvesti izravno iz DMR-a. Oni se nazivaju osnovni reljefni parametri i dijele se na lokalne i regionalne (Olaya, 2009.). Evans (1972., 1980.), uz hipsometriju, navedene parametre smatra temeljnim pretpostavkama geomorfometrijske analize.

Introduction

This paper focuses on geomorphometrical analysis of certain basic parameters of the broader Duvanjsko polje relief (slopes, aspects, profile and planar curvature) and their importance as endogenous and exogenous geomorphic processes indicators. The analysis is mostly aimed at hillslopes of inclination > 2° located in the broader area of Duvanjsko polje mountainous rim, but also provides an insight into areas which correspond to the category of slopes with inclinations < 2°, which primarily refers to the Polje itself but also to some lesser terrain shapes outside the Polje.

Geomorphometry is the science of quantitative features of the Earth's surface (Pike et al., 2009). It represents an analytical and cartographic approach in the research of topographical features of Earth as well as an interdisciplinary field that mostly emerged from mathematics, natural sciences and informatics. Considering the object of geomorphometrical research, smaller terrain shapes are the object of specific geomorphometry while the terrain as a whole is the object of general geomorphometry. General geomorphometry is the basis for quantitative comparison of larger terrain shapes and includes methods that are not necessarily geomorphic (MacMillan, Shary, 2009). This paper employs the principles and methods of general geomorphometry, which applies to computer-based GIS analysis of the broader area of Duvanjsko polje within its observed limits.

Contemporary geomorphometrical analysis, based on GIS methods, refers primarily to the analysis of a digital terrain model (Franklin, 1987; Jordan, Csillag, 2001; Ganas et al., 2005; Smith, Clark, 2005). A digital terrain model is a mathematical representation of the Earth’s surface in either raster or vector shape, which also contains various strings of height values. Considering the spatial resolution, there are various raster terrain models, which directly influences the output results’ quality and precision. For the purposes of this paper, a digital raster terrain model of Duvanjsko polje and its borders hillslopes has been created by vectorization of contour lines from topographic maps scaled 1:25,000.

Geomorphometrical parameters can be directly drawn from DMR. They are called basic terrain parameters and are further divided into local and regional (Olaya, 2009). Evans (1972, 1980) considers these parameters, along with hypsometry, the basic premises of geomorphometrical analysis.
Objekt ovoga istraživanja su padine uzvišenja šireg područja Duvanjskog polja. Padine se mogu definirati kao reljefne plohe određene geografskim položajem, nagibom u odnosu na horizontalnu površinu, izloženošću (ekspozicijom) u odnosu na strane svijeta, te stupnjem zakrivljenosti (ekspozicijom) u odnosu na horizontalnu površinu, izloženošću (ekspozicijom) u odnosu na strane svijeta, te stupnjem zakrivljenosti (profile ili planarne). Recentni oblik padina posljedica je utjecaja niza prirodnih i društvenih faktora tijekom geneze i evolucije reljefa. Analizom morfometrijskih parametara moguće je dovesti u vezu značajke padina s geološkom građom i sastavom, ali i ostalim prirodnog geografskim čimbenicima (npr. klimatskim, pedološkim, vegetacijskim itd.). Numerički iskazani podaci morfometrijskih parametara, promatrali u lokalnom okviru, upućuju na posljedice djelovanja egzogenih geomorfoloških procesa, dok u regionalnom okviru upućuju na djelovanje endogenih (u prvom redu neotektonskih) morfostrukturnih procesa (Marković, 1983.).

Ciljevi ovoga istraživanja su: a) analiza morfometrijskih pokazatelja reljefa, b) analiza odnosa između morfometrijskih pokazatelja, strukturnih i litoloških značajki i c) sinteza svih analiziranih pokazatelja da bi se dobio detaljniji uvid u egzogeomorfološke i morfostrukturne značajke područja i omogućila procjena opsega i intenziteta dominantnih geomorfoloških procesa. Pri tome, posebna pažnja posvećena je detaljnoj geomorfometrijski analizi makromorfostrukture šireg područja Duvanjskog polja u okružju GIS-a na temelju digitalnog modela reljefa (DMR).

Istraživano područje

Duvanjsko polje jedno je od krških polja tzv. zone visokog krša Bosne i Hercegovine (Čičić, 2002.). Teritorij Bosne i Hercegovine nalazi se u središnjem dijelu Dinarida i zahvaća oko 25% ukupnog teritorija Dinarida. Do sada je, kako navode Čičić (2002.) i Lepirica (2009.), izvršeno više regionalizacija Bosne i Hercegovine prema različitim kriterijima. Prema geotektonskom kriteriju, područje Bosne i Hercegovine može se podijeliti na tri pojasa: Vanjske Dinaride, Središnje Dinaride i Unutarnje Dinaride. Takva geotektonska podjela Dinarida BiH zasnovana je prvenstveno na geografskom položaju i razlikama u litološkim i tektonskim odlikama izdvojenih zona, zatim na sličnim globalnim uvjetima geološke evolucije i orogenene, te specifičnostima u njihovom geotektonskom sklopu (Crčić, 2002.).

The objects of this research are hillslopes of the broader Duvanjsko polje area. Hillslopes can be defined as terrain levels defined by geographical location, inclination in relation to horizontal surface, aspect in relation to cardinal directions and the degree of curvature (profile or planar). Recent hillslopes’ shapes are the result of various natural and anthropogenic factors that have occurred during genesis and evolution of the terrain. By means of morphometric parameters analysis it is possible to establish a relation between hillslope features and geologic characteristics, as well as other natural and geographical factors (such as climate, soil, vegetation, etc.). Numerically expressed morphometric parameters data observed in local context give insight into the effects of exogenous geomorphological processes while, in the regional context, they give insight into the effects of endogenous (primarily tectonic) morfostructural processes (Marković, 1983.).

The aims of this research are: a) the analysis of morphometric terrain indicators, b) the analysis of the relation between morphometric indicators, structural and lithological features, and c) the synthesis of all the analyzed indicators in order to gain better insight into the exogeomorphological and morfostructural features of the observed area, as well as enable an estimation of dominant geomorphologic processes’ size and intensity. Special attention was given to a detailed geomorphometrical macro-morfostructures analysis of the broader Duvanjsko polje area in GIS environment by means of digital terrain model (DMR).

The researched area

Duvanjsko polje is a karst polje in the so-called "high karst zone" of Bosnia and Herzegovina (Crčić, 2002.). Bosnia and Herzegovina is located in the central Dinaric Alps, and includes some 25% of the overall Dinaric Alps area. So far, as Crčić (2002) and Lepirica (2009) point out, a number of different regionalizations of Bosnia and Herzegovina have been conducted, based on different criteria. Concerning geotectonic criteria, the area of Bosnia and Herzegovina can be divided into three regions: Outer Dinaric, Middle Dinaric and Inner Dinaric Alps. Such geotectonic regionalization is based mostly on geographical location and differences in lithological and tectonic features of isolated zones, similar global conditions of geologic evolution and orogenesis, as well as on various specific features of their geotectonic context (Crčić, 2002.).
Prema ovoj podjeli, Duvanjsko polje s okolnim područjem dio je Vanjskih Dinarida, a u neposrednoj okolici polja, između planina Ljubuše i Raduše prolazi granica između Vanjskih i Središnjih Dinarida. Iako se kod određivanja tektonskih jedinica primjenjuju različiti kriteriji, ono što je neosporno kod Duvanjskog polja je da se ono u cijelosti nalazi u području Vanjskih Dinarida, odnosno u "zoni visokoga krša" (Sl. 1.).

U morfološkom smislu, istraživano područje vrlo je raznoliko. Relativna visinska razlika iznosi 839 metara – najniže je područje dna Duvanjskog polja, na 855 mmv, a najviše se nalazi na visini od 1694 m na vršnom dijelu planine Tušnice. Reljefno se ističu dijelovi planinskih masiva i zaravnja koji okružuju Duvanjsko polje (Sl. 1.). Izmjene Duvanjskog polja i Buškog blata, na JZ dijelu istraživanih područja, nalazi se planina Midena, koja predstavlja dio prostorne Grabovičke zaravne sastavljene od brojnih konkavnih oblika (međuprostori između konkavnih oblika), s istaknutim blago izduženim grebenom, koji se pruža iz smjera SZ prema JI doMesihovine (Papeš, Raić, 1968.). JI od Duvanjskog polja nalazi se planina Vran, s karakterističnim smjerom (prikazano stijenom deformed by the ice and subsequently karstic corrosion. Located to the south of Vran is the Lib Mountain. There is a very deep river shaped valley, formed after the ice had melted and the karst terrain had corroded, located between the Lib and the Vran Mountain, or between Kongora and Blidinje Lake.

Tušnica Mountain is located along the northwestern rim of Duvanjsko polje (stretching from east to west, similar to Vran). The range of Ljubuša is positioned along the elongated northeastern side of the Polje, its slopes representing the contact area with the Polje. Borders between the Polje and its surrounding mountainous rim are not clearly defined at all points. This primarily refers to the hillside southwest from Tomislavgrad, southwestern slopes shaped by Cretaceous sediments at the contact point between Ljubuša and far western part of Vran, and the contact area between the southeastern part of Grabovica and the Polje (Fig. 1).

As for the geotectonic location, the situation is more complex. Papeš (1985) notes nine different tectonic units in the southwestern Bosnia area, five of which are located in the vicinity of Duvanjsko
Kriteriji za izdvajanje tektonskih jedinica bili su slijedeći (Čičić, 2002.): rasjedni (navlačni) kontakti, oblik bora i rasjeda, facijalni razvoj istodobnih stratigrafskih članova, broj stratigrafskih članova i njihov međusobni odnos (kontinuitet u taloženju ili diskordancija i stratigrafske praznine).

Na temelju navedenih kriterija izdvojeno je šest tektonskih jedinica koje su od neposrednog značaja za istraživano područje: Dinarska, Glamočka, Cincarska, Malovanska, Ljubuška i Zavelimska (Sl. 2.).

Considering the fact that his regionalization did not include the southern part of the area researched in this paper, the regionalization has been complemented with Tumač OGK (list Imotski, Papeš, Raić, 1968). The criteria for tectonic units' selection are the following (Čičić, 2002): fault contacts, the shape of folds and faults, facial development of stratigraphic units of the same age, the number of stratigraphic units and their relation (continuity or discordance of sedimentation and stratigraphic voids).
Duvanjsko polje je građeno od naslaga miocenske starosti (De Leeuw et al., 2011) koje su uz rubne dijelove (npr. JI dio polja oko Kongore) ili uz riječne tokove prekrivene kvartarnim nanosima. Rubni planinski okvir je složenije građe: prevladavaju vapnenci i dolomiti jurske i kredne starosti, s mjestimično prisutnim manjim područjima naslaga terciarne starosti Tušnice na sjeveru, Ljubuša i Vrana na sjeveru, I i JI, Grabovičke zaravni i Midene planine na JZ, Liba na JI te Mesihovine na jugu (Sl. 3.).

Based on the aforementioned criteria six tectonic units of prime importance for the researched area have been isolated: Dinara, Glamoč, Cincar, Malovan, Ljubuša and Zavelim (Fig. 2).

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Based on the aforementioned criteria six tectonic units of prime importance for the researched area have been isolated: Dinara, Glamoč, Cincar, Malovan, Ljubuša and Zavelim (Fig. 2).

Duvanjsko polje is made from various sediments from Miocene, covered in Quaternary sediments at its rims (e.g. southeastern part of the Polje, near Kongora) and near riverbeds (De Leeuw et al., 2011). The mountainous rim is of more complex structure: the main type of rock is limestone and
JZ granica polja, uz Grabovičku zaravan, proteže se gotovo pravocrtno; uzduž nje na SZ dijelu spuštaju se prema SI slojevi vapnenaca; u središnjem dijelu strmo dok se duž JZ dijela spuštaju u obliku terasa. Zbog gotovo pravocrtnog protezanja graničnog područja, kao i postojanja strmog odsjeka u njegovom središnjem dijelu, može se zaključiti kako je rub polja nastao tektonsko (spuštanje); noviji denudacijski procesi neznatno su ga promijenili (Roglić, 1940.).

Duž SI ruba polja, na topografski jasno izraženoj granici, prisutan je kontakt slatkovodnih slojeva građenih od lapora i vapnenaca miocenske starosti (Papeš, 1967.) prekrivenih tankim površinskim pedološkim slojem polja, s krednim vapnencima Ljubuše. Samo oko Mokronoga vapnenac je pokriven mladim naslagama; u središnjem dijelu na području potoka Sazlivoda kraj Vedašića, pojavljuju se svijetlosivi dolomiti donjokredne starosti, u izmjeni s vapnencima iste starosti.

Rubovi polja na SZ i JI i po morfologiji i tektonsko-petrograškim karakteristikama daleko su zamršenijsije građeni, a planinski masivi i brežuljkasta područja poput Gromila slopes sreću se s srednjim vapnencima Ljubuše. Brežuljkasto područje oko Tomislavgrad na SZ). Brežuljkasto područje oko Tomislavgradgrađeno je od slatkovodnog lapora, peščenjaka i breča, koje u podnožju talože grubi materijal u velikim količinama. Iz navedenog proizlazi da je SZ dio Duvanjskog polja, posebno u dijelovima koji su u blizini Tušnice, područje dolomite of Jurassic and Cretaceous period, with smaller local examples of Tertiary sediments near Tušnica in the north, Ljubuša and Vran in the east, southeast and northeast, Grabovica plateau and Midena Mountain in the southwest, Lib in the southeast and Mesihovina in the south (Fig. 3).

The southwestern border of the Polje, near Grabovica plateau, is stretched almost linearly; along the border, in its southwestern part, layers of limestone descend towards southeast, steeply in the middle section, and in the shape of terraces in the southwestern section. Due to the near-linear direction of the bordering area, as well as the existence of a steep cutoff in the middle section, it can be concluded that the bordering area of the Polje was created tectonically (by sinking); more recent denudation processes have only slightly changed it (Roglić, 1940.).

Along the southeastern rim of the Polje, at the topographically clearly defined border, there is a contact between fresh-water limestone and marl layers from Miocene period (Papeš, 1967) covered by a thin layer of soil, along with Cretaceous limestone of Ljubuša. The limestone is covered in more recent layers only near Morkonog; in the middle section, at the Sazlivoda creek near Vedašić, light-gray dolomite from Early Cretaceous period appears along with limestone of the same age.

Borders of the polje at its northwestern and southeastern part are far more complex in terms or morphology and tectonic or petrographic features, with mountainous ranges and surrounding hills shaped like peninsulas protruding into the area (Lib Mountain in the southeast and the hillside near Tomislavgrad in the northwest). Tomislavgrad hills are made up of fresh-water marl, sandstone, clay with coarse sandstone and Miocene conglomerates (Papeš, 1967). These layers are fairly thick.

Tušnica Mountain is the most prominent section of the northwestern part of the Polje. Along with hard gray limestone of Late Cretaceous, Tušnica contains light-red limestone, marl, conglomerates and breccias, which make up its southwestern part. Significant amount of decay and breakage in the rock formations indicate that Tušnica had been an area of strong tectonic movements. The position of fresh-water marl indicates intensive geotectonic movements as well: the layers of Gromila slopes are inclined as much as 45°. The raising of Tušnica Mountain occurred before the second lake-formation period during the transition period between Late and Early Miocene (De Leuw et al., 2011). Water torrents from the zones made...
novijega poprečnog nabiranja i izdizanja koje je na veće visine izdiglo slatkovodne nanose koji imaju veliki pad prema dolini polja (ROGLIĆ, 1940.).

Ji rub polja mnogo je jednostavnije građe nego SZ. Planina Lib poput poluotoka prodire u nizinu polja. Prema podacima OGK-a (PAPEŠ, RAJĆ, 1968.), sastavljena je od vapnenaca kredne i jurske starosti. Od posebne su važnosti zone lapora pliocenske starosti, kao hidrološke barijere, koje se nalaze na vršnim dijelovima SL padine, uz rasjednu liniju, iz kojih izviru vrela koja selu Kongori daju vodu (ROGLIĆ, 1940.).

up of light-red limestone, breccias, conglomerates and the remaining marl have formed ravines and accumulated large amounts of rough material in the basins. This all indicates that the northwestern areas of Duvanjsko polje, especially those closer to Tušnica, are the areas of recent transversal folding and raising which elevated the fresh-water layers, which now fall steeply towards the base of the Polje (ROGLIĆ, 1940).

The southeastern part of the polje is of much simpler structure. Lib Mountain protrudes into the polje like a peninsula. According to the data
**Metodologija**

**Proces obrade podataka**

Proces obrade podataka temeljio se na analizi digitalnog modela reljefa, koji je za potrebe ovoga rada izrađen metodom automatske vektorizacije izohipsa s topografskih karata. Korišteno je devet listova TK 25 Vojnogeografskog instituta iz Beograda, od kojih su neki vektorizirani potpuno, a drugi djelomično, ovisno o obliku istraživanih područja. Dobiven je DMR rasterske GRID strukture, veličine piksela 25 metara. On se nalazi unutar četverokuta dimenzija 26 km u smjeru istok – zapad i 26 km u smjeru sjever – jug. S obzirom na to da tijekom izrade modela dolazi do pogrešaka, moguće su manje pogreške u izlaznim rezultatima, jer dobiveni podaci nisu uspoređivani s drugim digitalnim modelima reljefa. Obično se uzima da je visinska točnost jednaka 1/4 ili 1/5 ekvidistance (Ackermann, 1994.), pa bi visinska točnost dobivenog DMR-a bila 2 – 2,5 m. Prema Ackermann (1994.), razmak između lomnih točaka može iznositi najviše 40 m.

**Digitalni model reljefa šireg područja Duvanjskog polja**

Za potrebe geomorfometrijske analize istraživanog područja pomoću alata GIS-a bilo je nužno izraditi digitalni model reljefa. Razlozi izrade DMR-a su nedostupnost besplatnog detaljnijeg DMR-a, bolja kvaliteta u odnosu na dostupne DMR-e i precizniji izlazi podaci. Općenito, model je objekt ili koncept koji se koristi za predstavljanje neke pojave u prostoru, tj. umanjen prikaz stvarne situacije pretvoren u razumljiv oblik (Meyer, 1985. prema: Li et al., 2005.). Za prostorne analize koriste se različiti digitalni visinski modeli Zemljine površine (DEM). Iako postoji nejasnost u terminologiji, općenito se dijele na digitalne modele reljefa (Digital terrain model) i digitalne modele površina (Digital surface from OGK (Papeš, Račić, 1968), it is made up of limestone from Cretaceous and Jurassic period. Especially significant are the areas of Pliocene marl, which function as hydrological barriers located at the peak sections of the northeastern slope, along the fault line. They feature water wells that provide the village of Kongora with water (Roglić, 1940).

**Methodology**

**Data processing**

Data processing was based on the digital terrain model analysis, which, for the purposes of this paper, employed the method of topographic maps’ contour lines automatic vectorization. Nine papers of TK-25 maps made by the Military-geographic institution in Belgrade were used, some of which have been vectorized completely and other partially, depending on the shape of the researched area. A DMR of raster GRID structure was made, with a 25 meters pixel size. It is located within a square measuring 26 km from east to west and 26 km from south to north. Considering that the process of model generation usually experiences errors, a smaller error might have occurred in the output data, especially since the data have not been compared to that of other similar models. It is usually assumed that the vertical precision equals 1/4 or 1/5 of the equidistance (Ackermann, 1994), so the vertical precision of the current DMR model is 2-2.5 meters. According to Ackermann (1994), the distance between crucial points can amount to 40 meters at most.

**Digital terrain model of the broader Duvanjsko polje area**

For the purpose of the researched area’s geomorphometrical analysis by means of GIS tools, it was necessary to develop a digital terrain model. The reasons for the DMR development are: unavailability of a more detailed DMR, better quality level compared to the available DMR, and more precise output data.

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1 SRTM (Shuttle Radar Topographic Mission) – a digital height model developed by NASA. It is a positive turnover in the height data availability for the majority of the world. One SRTM paper includes the space of 5x5 degrees of the Earth's surface. SRTM 90m has a 90 meters resolution on the Equator and the vertical error margin of 16 meters. It is available on the internet pages of CGIAR-CSI (Consultative Group on International Agricultural Research - Consortium for Spatial Information).
model), ovisno o tome prikazuju li samo reljef ili uključuju biotičke i antropogene sadržaje.

Proces izrade digitalnog modela reljefa uključivao je sljedeće korake:

1. Skeniranje analognih topografskih kartara – pretvaranje kartara u digitalni oblik bez prostorne reference.
2. Georeferenciranje i transformaciju – referentne točke uzete su s topografskih kartara, čime su karte smeštene u geografski prostor. S obzirom na to da se radilo o skeniranim kartama korištena je afina transformacija polinoma prvog reda.
3. Vektorizaciju izohipsi i dodavanje atributa (podataka o visinama s topografskih kartara) – automatska vektorizacija izohipsa uključivala je odstranjivanje šumova, skeletiranje (stanjivanje), poboljšanje čvorova, praćenje linija, spajanje segmenta i topološku rekonstrukciju.
4. Izradu TIN-a – vektorskog modela reljefa, koji se sastoji od točaka, linija i trokuta, te predstavlja temelj izrade rasterskog modela reljefa. Na osnovi lomnih točaka (sastavni dio izohipse) konstruirana je triangulacijska nepravilna mreža.
5. Izradu DMR-a – rasterskog modela reljefa. Digitalni model reljefa temeljni je akronim koji se danas koristi u literaturi koja se tiče GIS-a, daljinskih istraživanja i srodnih područja. Digitalni model reljefa predstavlja digitalni prikaz Zemljine površine, ali bez vegetacije ili produkata antropogenog djelovanja. Dakle, DMR prikazuje samo "temeljnu" ili "golu" površinu Zemlje, odnosno reljef.

Korištenje alata GIS-a u analizi DMR-a omogućilo je stvaranje novih podataka i njihovu analizu, a izlazni podaci u konačnici su bili precizniji.

Generally, a model is an object or a concept used to represent various entities in the geographic space, i.e. a smaller representation of the real situation transformed into an understandable form (Meyer, 1985, cf. Li et al., 2005). Various height-related digital terrain models are used for spatial analyses (DEM). Although there is a certain degree of misunderstanding in general terminology, they are usually divided into digital terrain models (DMR) and digital surface models, depending on whether they represent reliefs only or include biotic and anthropogenic elements as well.

The process of digital terrain model generation included the following steps:

1. Scanning of analogue topographic maps – turning maps into a digital format without a spatial reference.
2. Georeferencing and transformation – referential points were taken from topographic maps, which means that the maps were transferred to geographic space. Since the maps were scanned, an affine transformation of first-degree polynomial was used.
3. Vectorization of contour lines and addition of attributes (height data from topographic maps) – automatic vectorization included removal of noises, thinning, nodes improvement, and segment merging and topological reconstruction.
4. TIN development – a vector terrain model, which is made up of points, lines and triangles, and represents a base for raster terrain model development. Based on the crucial points (an integral part of a contour line), an irregular triangulation grid was constructed.
5. DMR development – a raster terrain model. Digital terrain model is a basic acronym used in literature that refers to GIS, remote research and similar fields. DMR represents the shape of the Earth’s surface, but without vegetation or anthropogenic activity products. Therefore, DMR only shows the "basic" or "naked" Earth’s surface, i.e. relief.

The usage of GIS tools in the DMR analysis enabled new data creation and analysis, while the output data turned out more precise.
Visualization of the calculated data

All the cartographic addendums represent visual results of the digital terrain model analysis. In this paper, a number of visualization techniques were used to display the results:

1. Color selection for individual classes
2. Optimization of the output data's cell representation within the raster, which employed the "cubic convolution" method
3. The obtained results' overlap (at 30% transparency level) and terrain shading in order to create a more plastic relief impression and determine relations between the quantitative parameters and terrain morphology.

Discussion

Morphometric parameters analysis

1. Slope analysis

Relief can be defined as a combination of hillslopes of various inclination categories (Bognar, 1990). Large parts of the Earth's surface are made of various types of slopes created by both endogenous and exogenous processes. This research applied the comprehensive approach, i.e. morphometric analysis of micro-relief shapes was not as important as macro-geomorphologic relations within the complete researched area were. Spatial distribution and specific slope categories coverage analysis is important since they represent significant indicators of the size and intensity of morphostructural and exogeomorphological processes (denudation or accumulation). These processes have affected the slopes' morphogenesis during the paleo-geomorphological period and their analysis indicates future effects of the aforementioned processes on relations between terrain raising and sinking, i.e. denudation and accumulation and their characteristics (Tab. 1).

For the purpose of inclination calculation, ArcInfo methods and algorithms were used. Inclination values are determined by use of software that calculates a maximal change rate of measured values between neighboring pixels. Conceptually, the function of inclination fits the slope and z-value

2 This method was used only during visualization, and not in calculating spatial extent of morphometric parameters, because it changes the value within a pixel.
plohu i z-vrijednosti unutar područja od 3 x 3 piksela koje okružuje središnji piksel, a vrijednost nagiba ove plohe izračunava se pomoću tehnike prosječnog maksimuma (Burrough, McDonell, 1998.). Mreža koju čine čelije jednakih dimenzija, poravnana je uzduž geografskih osi x (zapad – istok) i y (sjever – jug).

Stopa promjene u smjeru x stranice npr. za "h_e" izračunava se algoritmom:

\[ h_x (dz/dx) = \frac{(h_c + 2h_f + h_i) - (h_a + 2h_d + h_g)}{8 * d} \]

Stopa promjene u smjeru y stranice za "h_e" izračunava se algoritmom:

\[ h_y (dz/dy) = \frac{(h_g + 2h_h + h_i) - (h_a + 2h_b + h_c)}{8 * d} \]

Izračunom stopa promjene u x i y smjeru, nagib za čeliju "h_e" izračunava se primjenom sljedećeg izraza:

\[ N = \sqrt{h_x^2 + h_y^2} \]
\[ N(°) = ATAN (N) \]

Radi pojednostavljanja analize i interpretacije podataka, primijenjena je geomorfološka klasifikacija nagiba padina (Tab. 1.).

Nagibi manji od 2° karakteristični su za najveći dio Duvanjskog polja zbog čega imaju i najveći prostorni obuhvat (s 35,2% udjela, Tab. 2.), međutim, manja područja takvog nagiba pojavljuju se i na okolnim planinama. Prije svega karakteristični su za korozijsku zaravan Podine od Mokronoga do Lipa, a javljaju se i na pojedinim zaravnima planine Ljubuše te na Grabovičkoj zaravni (Sl. 5.).

Druga kategorija nagiba (2 – 5°, 13,58%) u pravilu se javlja na kontaktnim dijelovima polja i okolnog područja, gdje postoji blagi prijelaz, prekriven naslagama koluvijalnog i deluvijalnog podrijetla, iz zaravnjenog dijela polja u strmiji planinski okvir (Tab. 2., Sl. 5.). Na rubovima polja ovi nagibi najrasprostranjeniji su sjeverno od Tomislavgrad, gdje polje postupno prelazi u brežuljkasto područje, te na prijelaznom području u blizini sela Bukovice gdje se slojevi stepenastu uzdižu prema Midenoj planini. Također, velika područja planine Ljubuše i Grabovičke zaravni pripadaju ovoj kategoriji. Na Ljubuši se ovi nagibi javljaju na područjima uvala, koje su u prošlosti bile sezonski naseljene i agrarno vrednovane u ljetnom dijelu godine. Unutar ove kategorije nagiba nalaze se i blago položene SZ padine izgrađene u stijenama kredne starosti na području kontakt Ljubuše i krajnjega zapadnog dijela

within the area of 3x3 pixels surrounding a central pixel, and the value of this plane’s inclination is calculated using the average maximum technique (Burrough, McDonell, 1998). The grid composed of equally sized neighboring cells is leveled along geographical axes x (west - east) and y (north - south).

The change rate directed towards the x-axis for e.g. "h_e" is calculated using the following algorithm:

\[ h_x (dz/dx) = \frac{(h_c + 2h_f + h_i) - (h_a + 2h_d + h_g)}{8 * d} \]

The rate of change towards the y-axis for e.g. "h_e" is calculated using the following algorithm:

\[ h_y (dz/dy) = \frac{(h_g + 2h_h + h_i) - (h_a + 2h_b + h_c)}{8 * d} \]

By calculating the change rates in x- and y-directions, the "h_e" cell inclination is then calculated as follows:

\[ N = \sqrt{h_x^2 + h_y^2} \]
\[ N(°) = ATAN (N) \]

Geomorphologic classification of slope inclination has been used in order to simplify data analysis and display (Tab. 1.).

Slopes with less than 2° inclination are predominant in the largest part of Duvanjsko polje and therefore have the largest spatial coverage (35.2% of all the slopes, Tab. 2.). However, smaller areas of identical slope inclination also appear in the bordering mountains. They are primarily present in the corrosion plateau of Podine, from Mokronoge to Lipa, at certain plateaus of Ljubuša Mountain, and on the Grabovica plateau (Fig. 5.).

The second inclination category (2-5°, 13.58%) is mostly present at contact sections between the Polje and surrounding areas, where there is a mild transition from the Polje to steeper mountainous rim covered in colluvial and diluvial layers (Tab. 2, Fig. 5). At the edges of the Polje such inclinations appear most frequently north of Tomislavgrad, where the Polje gradually shifts into hillside, and in the bordering area near the village of Bukovica, where layers gradually rise into Miden Mountain. In addition, great portions of Ljubuša and Grabovička plateau belong to this category. These types of slopes are present in Ljubuša basins, which were seasonally populated and agriculturally used during the summer period in the past. Areas that also belong to this inclination category are the mildly inclined northwestern slopes composed of Cretaceous rocks near the contact area between Ljubuša and far western part of Vran Mountain,
Geomorfološka klasifikacija nagiba, temeljena na dominantnim morfološkim procesima koji se aktiviraju ovisno o veličini nagiba, kao i odgovarajućim reljefnim oblicima, prihvaćena je od IGU-a (International Geographical Union, 1968.).

| Nagib (°) | Karakteristike geomorfoloških oblika i procesa |
|----------|-----------------------------------------------|
| < 2 | Ravnica. Kretanje masa se ne zapažaju. Intenzitet spiranja minimalan |
| 2 – 5 | Blago nagnut teren. Spiranje slabo izraženo. Spiranje tala i pojave kliženja mogu biti značajne. |
| 5 – 12 | Nagnuti tereni. Pojačano spiranje i pojave kretanja masa. Do izražaja dolazi kliženje i tečenje materijala. Teren ugrožen padinskih procesima. |
| 12 – 32 | Značajni nagibi. Spiranje je intenzivno. Veoma snažni padinski procesi. Teren jako ugrožen spiranjem i pojavom kretanja masa. |
| 32 – 55 | Vrlo strm teren. Dominira odnošenje materijala. Akumulacijski materijal se tek mjestimično zadržava (tanki pokrivač). Padine su stjenovite i pretežito ogoljene. |
| > 55 | Strmci, litice (eskarpmani). Dominira osipanje i urušavanje |

**Tablica 1. Geomorfološka klasifikacija nagiba**
**Table 1 Geomorphologic classifications of slopes**

| Inclination (°) | Features of geomorphologic shapes and processes |
|----------------|-----------------------------------------------|
| < 2 | Plain. Mass movements are not evident. Soil wash intensity is minimal. |
| 2 – 5 | Mildly inclined terrain. Soil wash is weak. Soil wash and creep can be significant. |
| 5 – 12 | Inclined terrain. Relatively strong soil wash and mass movement. Accented soil creep and downhill flow of material. Terrain is compromised by slope processes. |
| 12 – 32 | Significant inclination. Soil wash is intensive. Very strong slope processes. Terrain significantly compromised by soil wash and mass movement. |
| 32 – 55 | Very steep terrain. Material removal is dominant. Material is accumulated only sporadically (a thin layer). Slopes are rocky and mostly barren. |
| > 55 | Cliffs, escarpments. Dispersal and collapsing are dominant. |

Izvor / Source: IGU, 1968.

Vrana, prijelazno područje od JI dijela polja prema planini Vran te niži dijelovi padina planine Lib na kontaktnom području s poljem (Sl. 5.).

Također, velika područja planine Ljubuša i Grabovičke zaravni pripadaju ovoj kategoriji. Na Ljubuši se ovi nagibi javljaju na područjima uvala, koje su u prošlosti bile sezonski naseljene i agrarno vrednovane u jenom dijelu godine. Unutar ove kategorije nagiba nalaze seiblago položene SZ padine izgrađene u stijenama kredne starosti na području kontakta Ljubuša i krajnjeg zapadnog dijela Vrana, prijelazno područje od JI dijela polja toward the Vran Mountain, and lower slopes of Lib Mountain at the contact area with the Polje (Fig. 5).

Most areas of Ljubuša Mountain and Grabovica plateau belong to this category as well. On Ljubuša Mountain, these slopes appear in uvalas, which in the past were seasonally populated and agriculturally used during the summer. Within this slope category are the low-inclined northwestern slopes of Cretaceous period in the contact area between Ljubuša Mountain and far western Vran as well as the contact area between southeastern part of polje and Vran, and the lower parts of...
Inclinations between 5° and 12° are the second most frequent, following the < 2° category and making up for 26.39% of the total surface (Tab. 2, Fig. 5). They are almost evenly distributed along the entire mountainous rim of the Polje, mostly at lower parts of the slopes or at limestone plateaus of Grabovica, Ljubuša and Lib Mountains (Fig. 4).

On higher slopes of Tušnica, Jelovača and Lib Mountains, which are steeper due to neo-tectonic movements, the most frequent category of slopes is 12°-32° (23.79%), while higher inclination categories appear less frequently (32-55° with 1.07%, and > 55° with 0.003%). Apart from the aforementioned areas of Tušnica, Jelovača and Lib, slopes inclined 12-32° appear on relatively large areas (Tab. 2). They can be found on steep sides' higher parts near cliffs, on lower parts of slopes with significant fault tectonic activities, near the sides of deeper ravines and karst sinkholes and, finally, in transitional areas between the flat parts of
Ova kategorija nagiba dominantna je duž velikog dijela jugozapadnog kontaktog dijela Grabovičke zaravni i polja, od prijevoja Privala do sela Bukovice, gdje prelazi u tektonski i reljefno razdrobljeno valovito područje Grabovičke zaravni, koje se od jugozapada stepenastom spušta prema sjeveroistoku i nestaje uz rub polja. Granica sjeveroistočnog dijela polja i planine Ljubuše također je dobro definirana ovom kategorijom nagiba, osobito od sela Kuka do Letke, gdje ovaj strmi rub lokalno stanovništvo naziva "Greda". Na kanjonskim stranama Šujice izmjenjuju se nagibi od 12 do 32° i od 32 do 55° (Sl. 5.).

5.). Ova kategorija nagiba dominantna je duž velikog dijela jugozapadnog kontaktog dijela Grabovičke zaravni i polja, od prijevoja Privala do sela Bukovice, gdje prelazi u tektonski i reljefno razdrobljeno valovito područje Grabovičke zaravni, koje se od jugozapada stepenastom spušta prema sjeveroistoku i nestaje uz rub polja. Granica sjeveroistočnog dijela polja i planine Ljubuše također je dobro definirana ovom kategorijom nagiba, osobito od sela Kuka do Letke, gdje ovaj strmi rub lokalno stanovništvo naziva "Greda". Na kanjonskim stranama Šujice izmjenjuju se nagibi od 12 do 32° i od 32 do 55° (Sl. 5.).

the Polje and bordering mountainous (Fig. 5). This category is very dominant along a great section of southwestern contact area between the Grabovica plateau and the Polje, from the Privala notch to the village of Bukovica, where it shifts into a tectonically and geologically fragmented Grabovica plateau, which progressively lowers from the northwest to the northeast and gradually disappears near the edge of the Polje. The northeastern border between the Polje and the Ljubuša Mountain is also well defined within this inclination category, especially concerning the villages of Kuk and Letka, where the locals have named this steep edge "Greda".

Figure 5 The map of slope inclinations
Što se najviših vrijednosti nagiba tiče, nagibi od 32 do 55° prevladavaju uglavnom na višim dijelovima padina uz hrptove planinskih uzvišenja (izuzetak su područja s izraženom rasjednom tektonikom na područjima Tušnica i Jelovače, gdje je ova kategorija zastupljena i na nižim dijelovima padina) te uz kanjonske strane Šujice. Prilikom terenskog izlaska nagibi najviše kategorije (> 55°) uočeni su na litici planine Lib iznad Borčana (Sl. 5., Sl. 6.), te mjestimično na vrlo strmim stranama urušnih ponikava na području Grabovičke zaravni (Sl. 5.).

2. Analiza ekspozicija

Ekspozicija se može shvatiti kao orijentacija padine s obzirom na strane svijeta. Pri tome se kut orijentacije određuje najčešće od smjera sjevera u smjeru kazaljke na satu. U konceptualnom smislu, funkcija ekspozicije odnosi se na izražen vrijednosti ekspozicije središnjeg piksela u odnosu na osam susjednih (mreža piksela 3 x 3). Smjer prema kojem je ploha okrenuta predstavlja ekspoziciju za središnji piksel (BURROUGH, McDonell, 1998.).

### Tablica 2. Kategorije i prostorni obuhvat nagiba

| Nagib (°) | Površina (m²) | Udio (%) |
|----------|---------------|----------|
| < 2      | 129494800,0   | 35,160   |
| 2-5      | 50021200,0    | 13,582   |
| 5-12     | 97188800,0    | 26,389   |
| 12-32    | 87633200,0    | 23,794   |
| 32-55    | 3948000,0     | 1,072    |
| >55      | 11600,0       | 0,003    |
| Ukupno   | 368297600,0   | 100,000  |

| Inclination (°) | Area (m²) | Portion (%) |
|-----------------|-----------|-------------|
| < 2             | 129,494,800.0 | 35.160      |
| 2-5             | 50,021,200.0  | 13.582      |
| 5-12            | 97,188,800.0  | 26.389      |
| 12-32           | 87,633,200.0  | 23.794      |
| 32-55           | 3,948,000.0   | 1.072       |
| >55             | 11,600.0      | 0.003       |
| Total           | 368,297,600.0 | 100.000     |

(The Wall). In Šujica canyon 12-32° and 32-55° inclination categories interchange (Fig. 5).

Regarding the highest inclination values, 32-55° inclinations most often prevail in higher parts of slopes near mountain crests (with the exception of areas with significant fault tectonics near Tušnica and Jelovača, where this category appears in lower parts of slopes as well) and near the canyon sides of Šujica. During the field research, highest category inclinations (> 55°) were recorded on a Lib Mountain cliff near Borčane (Fig. 5, Fig. 6) and, in places, on very steep sides of collapsed dolines on Grabovica plateau (Fig. 5).

2. Aspect analysis

Aspect can be defined as slope orientation in relation to cardinal directions. Orientation angle is usually measured clockwise from the north. Conceptually, the function of aspect is the calculated aspect value of a central pixel in relation to its eight neighboring pixels within a 3x3-pixel grid. The direction to which a surface is orientated represents the aspect of the central pixel (Burrough, McDonnell, 1998).
Stopa promjene u x smjeru za čeliju "he" izračunava se sljedećim algoritmom:
\[ h_x (dz/dx) = ((h_c + 2h_f + h_h) - (h_a + 2h_d + h_g)) / 8 \]

Stopa promjene u y smjeru za čeliju "he" izračunava se sljedećim algoritmom:
\[ h_y (dz/dy) = ((h_g + 2h_h + h_i) - (h_a + 2h_b + h_c)) / 8 \]

Uzimajući stopu promjene u x i y smjeru za čeliju "he", ekspozicija se izračunava pomoću algoritma:
\[ E = 57.29578 * \text{ATAN}^2 (h_y, - h_x) \]

Nakon toga vrijednost ekspozicije konvertira se u stupnjeve (0 – 360°).

Na istraživanom području ekspozicije indirektno utječu na promjene vezane uz denudaciju, koroziju i sedimentaciju padinskih trošina, kao i hidrološke procese na padinama. Primjerice, povećano kratkovalno zračenje na geomorfološke procese vrlo je značajan jer različito eksponirane padine primaju različitu količinu kratkovalnog zračenja, što utječe na karakteristike klimatskih elemenata kao egzogeno-geomorfoloških agensa.

U skladu s prividnim kretanjem Sunca preko obzora tijekom dana ili različitih godišnjih doba, mijenja se i intenzitet kraticvalnog Sunčeva zračenja na padinama. Na sjevernoj hemisferi najviše Sunčeva zračenja primaju južne padine, a sjeverne najmanje. Istočno i zapadno eksponirane padine ozračene su u manjoj mjeri od južnih, a u većoj od sjevernih; istočne najviše zračenja primaju ujutro, a zapadne u predvečerje (Šegota, Filipčić, 1996.). Utjecaj ekspozicija na geomorfološke procese vrlo je značajan jer različito eksponirane padine primaju različitu količinu kratkovalnog zračenja, što utječe na karakteristike klimatskih elemenata kao egzogeno-geomorfoloških agensa.

In accordance with the apparent motion of the Sun across the horizon during the day or different seasons, the intensity of shortwave radiation on hillslopes changes as well. On the northern hemisphere, most of the radiation is received by southern hillslopes and the least by northern. Generally, eastern and western slopes are less exposed than southern slopes but more than northern; eastern slopes receive most of the radiation in the morning and the western slopes in the dusk (Šegota, Filipčić, 1996). The influence of aspect on geomorphologic processes is very important since differently exposed slopes receive different shortwave radiation, which affects the climate elements as exogenous and geomorphologic agents.

In the researched area, aspects indirectly influence the changes in denudation, corrosion and sedimentation of slope material, as well as hydrological processes on the slopes. For example, an increased amount of shortwave radiation on the slopes exposed to the southern quadrant (southwest, south and southeast) directly influences evaporation and transpiration increase, which leads to water shortage during the dry season (especially on limestone-based areas), and the result is a decrease in the plants' number and size on the slopes, i.e. much scarcer vegetation. Scarce vegetation enables more rapid loss of water from the soil and greater surface drainage, which intensifies the denudation process. On northern slopes, the moist is contained in the soil for longer periods of time, which positively affects vegetation development and provides more acceptable conditions for creation and development of soils. Long term processes of soil wash, amongst other denudation processes, can result in increased inclinations in higher parts of slopes (more intense denudation) and decreased inclinations in lower
Increased inclination is evident in higher mountain areas and sedimentation in the lower areas. This is combined with prolonged processes of soil wash, creep and collapsing, enhanced by lithological features and significant daily and seasonal temperature amplitudes. General aspect aptitude: N = cold aspect; NE and NW = moderately cold aspect; E and W = neutral aspect; SE and SW = warm aspect; S = very warm aspect.
Može se uočiti lučno izvijanje morfostrukture.

Slika 7. Zapadna i SL padina Liba, odvojene vršnim grebenom.

Figure 7 West and southeast hillslopes of Lib Mountain separated by a peak ridge.

of the southern quadrant with warm and very warm orientation (southeast, south and southwest) make up for 46.22% of the total area. Those are the areas of Ljubuša Mountain, south and southwest slopes of Vran opposite to southeast and east slopes of Lib, southwest and south slopes of Lib, Mesihovina, large parts of Grabovica plateau, and southern slopes of Tušnica and Jelovača (Fig. 8).

A smaller portion (31.90%, Tab. 3, Fig. 8) refers to slopes with moderately cold and cold aspects (northwest, north and northeast), such as the far northeastern slope of Grabovica plateau, which mostly descends steeply toward the Dušanjsko polje. In addition, large areas with such aspect are present on the slopes of Vran, opposite to Ljubuša, the slopes of Mesihovina opposite to Lib and in some parts of Tomislavgrad hills, and Tušnica and the central part of Ljubuša (Fig. 8).

Može se uočiti lučno izvijanje morfostrukture.

A bend in the morphostructure is also visible.
Udio neutralnih ekspozicija (W i E) u istraživanom području iznosi 21,88% (Tab. 3., Sl. 8.). Ove ekspozicije posljedica su mjestimičnih promjena dinarskog smjera pružanja morfostrukture u smjer S – J uzrokovanih izvijanjem tektonskih struktura. To se osobito odnosi na zapadnu i SE padinu Liba (Sl. 7., Sl. 8.) i istočne padine Tomislavgradskog pobrđa (Sl. 8.).

The portion of the aspects that fall into the neutral category (western and eastern) in the researched area amounts to 21.88% (Tab. 3, Fig. 8). Such aspects are a consequence of local changes in Dinaric Alps morphostructures’ extension from their general north-south direction, caused by bending of tectonic structures. This is primarily evident on western and southeastern slopes of Lib Mountain (Fig. 7, Fig. 8) and the eastern Tomislavgrad hills slopes (Fig. 8).
3. Analiza zakrivljenosti padina

Pojam zakrivljenosti padine odnosi se na njezin geometrijski oblik. Oblak padine rezultat je denudacijskih i akumulacijskih procesa, uzrokovanih endogenim i egzogenim geomorfološkim agensima.

Konveksne padine (ili dijelovi padina) indikator su pozitivnih tektonskih pokreta (izdizanje) povezanih s dominacijom denudacijskih procesa čiji intenzitet raste s porastom dužine padine. Površine padine ili dijelovi padina upućuju na prostorno uravnotežene denudacijske uvjete, npr. padina se povlači paralelno ili se materijal jednolično kreće po padini. Konkavne padine (ili njihovi dijelovi) indikator su negativnih tektonskih pokreta (spuštanje) povezanih s pojačanom akumulacijom padinskog materijala (Dikau et al., 2004.).

S matematičkog aspekta, zakrivljenost se definira kao odstupanje geometrijskog objekta.
od ravnine. Zakrivljenost je inverzna radijusu kružnice, odnosno izražava se izrazom $k = 1/R$. S porastom radijusa kružnice, zakrivljenost se smanjuje i obratno. Zakrivljenost predstavlja koeficijent odstupanja krivulje od pravca. Za točku u trodimenzionalnom prostoru moguće je izvesti beskonačan broj zakrivljenosti (Ohlmacher, 2007). Korištenjem metode 3 x 3 kvadrata, zakrivljenost se računa kao druga derivacija visinskih vrijednosti DMR-a, prema izrazu: $Z = Ax^2y^2 + Bx^2y + Cxy^2 + Dx^2 + Ey^2 + Fxy + Gx + Hy + I$. Postoji više vrsta zakrivljenosti, a u ovom radu se razmatraju profilna i planarna (Moore et al., 1993.; Ayalew, Yamagishi, 2004.).

Analizom DMR-a dobiven je niz vrijednosti zakrivljenosti iz kojeg su izdvojena tri tipa padina: konkavne, konveksne i pravocrtne. Veliki problem predstavljao je odabir metode za određivanje tipa zakrivljenosti. Dikau (1989.) zakrivljenost padina radijusa većeg od 600 m (k > 0,001666) na modelu rezolucije 20 m, smatra zanemarivom i takve padine ubraja u pravocrtne. Analogno tome, za korišteni model rezolucije 25 m, pravocrtnim padinama smatraju se padine radijusa većeg od 750 metara.

Granične vrijednosti određene su na sljedeći način:
1. granična vrijednost: vrijednost zakrivljenosti 0 – 0,001333;
2. granična vrijednost: vrijednost zakrivljenosti 0 + 0,001333;
3. granična vrijednost: maksimalna vrijednost niza.

Analize zakrivljenosti upućuju na karakter i intenzitet procesa koji djeluju na promjene u izgledu padina (ili njihovih dijelova). Ovakve analize, pogotovo specifične, upućuju na područja na kojima dolazi do relativno brzih promjena vrijednosti nagiba padina. U geomorfološkim istraživanjima ove analize mogu se primijeniti za izračunavanje i procjenu trendova endogenih (izdizanje ili spuštanje struktura) strukturanog i egzogenog procesa, npr. otopljenja i sedimentacije (pomoću planarne zakrivljenosti) pojačane denudacije i identificiranja otpornijih stijenskih kompleksa (pomoću profilne zakrivljenosti) (Kennelly, 2009.).

**Profilna zakrivljenost** odnosi se na zakrivljenost padina (ili njihovih dijelova) suži linija okomitih na izohipse, a njome se određuje stopa promjene nagiba za svaki piksel. Negativna vrijednost upućuje na konveksni uzdužni profil padine, a pozitivna na konkavni, dok vrijednost nula označava linearnu increases, the curvature decreases, and vice versa. Curvature represents a coefficient of a curve's divergence from a line. It is possible to make an unlimited number of curvatures for a certain point in a three-dimensional space (Ohlmacher, 2007). By using the method of 3x3 squares, curvature is calculated as the second derivative of DMR height values, using the following formula: $Z = Ax^2y^2 + Bx^2y + Cxy^2 + Dx^2 + Ey^2 + Fxy + Gx + Hy + I$. There are several different types of curvature, and this paper discusses profile and planar ones (Moore et al., 1993.; Ayalew, Yamagishi, 2004.).

During DMR analysis a number of curvatures' values was calculated, from which three types of slopes were determined: concave, convex and linear. The choice of a method for defining curvatures represented a significant problem. Dikau (1989) considers slope curvatures of radius greater than 600 meters ($k > 0.001666$) on a 20 meter resolution model negligible and categorizes them as linear. Analogously, in models with resolution greater than 25 meters, slopes with radius greater than 750 meters are considered linear.

Limiting values are defined as follows:
1. limiting value: curvature value of $0 – 0.001333$;
2. limiting value: curvature value of $0 + 0.001333$;
3. limiting value: maximum curvature value.

Curvature analysis points to characteristics and intensity of processes that cause changes in slopes' (or their parts) appearances. Such analyses, especially profile and planar curvatures analyses, indicate the areas in which changes in inclination values occur relatively fast. In geomorphologic research, these types of analyses can be employed to calculate and evaluate endogenous (raising or sinking) and exogenous geomorphologic processes' trends, such as soil wash and sedimentation (via planar curvature), enhanced denudation, and more resilient rock formations identification (via profile curvature) (Kennelly, 2009.).

**Profile curvature** refers to slope (or parts of slope) curvature along the lines perpendicular to contours and it is used to define the inclination change rate for each pixel. Negative values point to a convex longitudinal slope profile, while positive values indicate concave profile. The zero value points to a linear slope (Fig. 9). Profile curvature influences the speed of water flow and the speed of detritus movement down the slope.
Iz podataka o strukturi profilne zakrivljenosti (Tab. 4.) uočljiva je dominacija konveksnih i konkavnih padina na razini cijelog područja, međutim, bez velike razlike u udjelu (konveksne su nešto dominantnije, s 49,78%, dok udio konkavnih iznosi 47,89%). Pravocrtnе padine zastupljene s vrlo malim udjelom (od samo 2,34%), što upućuje na približnu ujednačenost smjerova tektonskih pokreta, i s njima povezanih egzogeomorfoloških procesa.

Iz prostornog prikaza tipova profilne zakrivljenosti (Sl. 10.) uočljivo je da konveksne padine prevladavaju na višim dijelovima uzvišenja, osobito uz grebene planinskih masiva i dijelove pobrđa (Lib, Mesihovina, zapadni dio planine Vran, Tušnica i Tomislavgradsko terciarno pobrđe), uz vršni dio strmog odsjeka na sjeveroistočnom rubu Grabovičke zaravni uz jugozapadni dio Duvanjskog polja, kao i na cijeloj Grabovičkoj zaravni. U slučaju Tušnice, korelacija s geološkim podacima upućuje

| Površina (m²) | Udio (%) |
|--------------|----------|
| Konveksne    | 118,866,400,0 | 49,78 |
| Linear       | 5,580,400,0 | 2,34 |
| Concave      | 114,355,600,0 | 47,89 |
| Ukupno       | 238,802,400,0 | 100,00 |

Profile curvature data (Tab. 4) shows an evident domination of convex and concave slopes in the entire area. However, there is no significant difference in their ratio (convex slopes are somewhat dominant, making up for 49.78%, while concave make up for 47.89%). Linear slopes are represented by a very small portion (only 2.34%), which indicates approximate balance between different tectonic movements’ directions and exogeomorphological processes that usually follow.

On the profile curvatures map (Fig. 10) it is noticeable that convex slopes dominate higher parts of mountains, especially near the ridges and some parts of hillsides (Lib, Mesihovina, western part of Vran Mountain, Tušnica and tertiary Tomislavgrad hills), near the steep cliff peaks of the Grabovica plateau at the southwestern part of the Polje, and on the entire Grabovica plateau. In the case of Tušnica, correlation with geological data indicates intensive positive neotectonic movement, which is supported by fresh-
na intenzivno djelovanje neotektonskih pokreta pozitivnog predznaka, što potvrđuje i položaj slatkovodnih lapora miocenske starosti na većim visinama. U skladu s time su i značajke morfoloških procesa, oblici i nagibi padina. Također, veliki areali konveksnih padina nalaze se na JI dijelu planine Ljubuše, prateći skretanje tektonskih struktura iz smjera SZ – JI u Z – I. Osobito izražena zona konveksnih padina proteže se uz viši dio linearno izdužene "grede" duž cijelog Sj dijela Duvanjskog polja te uz više dijelove kanjonskih strana Šujice na sjevernom dijelu istraživanog područja (Sl. 10.).

Za razliku od konveksnih, konkavne padine dominiraju na nižim dijelovima padina, uz rasjedne linije na cijelom istraživanom području, te uz niže dijelove bočnih strana jaruga planinskih masiva (Sl. 10.). To se može uočiti na nižim dijelovima uz kanjon Šujice, uz rasjednu liniju

Slika 10. Karta profile zakrivljenosti padina
Figure 10 The map of profile slope curvature

water Miocene marl position in higher areas. Morphological processes' characteristics, shapes and inclinations of slopes are in accordance with the aforementioned. In addition, relatively large areas of convex slopes are located in southeastern parts of Ljubuša Mountain, following the tectonic structures curve from northwest - southeast to west - east direction. An especially prominent zone of convex slopes stretches along higher parts of the linearly elongated "Greda" (The Wall) along the southeastern part of Duvansko polje, and along higher parts of Šujica canyon sides in the northern part of the researched area (Fig. 10).

Unlike convex slopes, concave ones mostly dominate lower parts of slopes, along the fault lines in the entire researched area and in lower parts of mountain valleys lateral sides (Fig. 10). This is particularly noticeable in lower parts of Šujica
koja razdvaja Tušnicu i Jelovaču, uz rasjed između sjevernih dijelova zapadnih padina Vran planine i Ljubuše i uz rasjed koji se lučno proteže cijelm središnjim područjem Liba u smjeru SZ – JI.

Profilne pravocrtne padine najzastupljenije su na dijelovima mladog tercijarnog Tomislavgradskog pobraća bližim Duvanjskom polju, na svim hipsometrijskim nivoima, tj. ne pokazuju pravilnost u vertikalnom rasporedu (Sl. 10.). Također, mogu se naći u krajnjem JI dijelu Grabovičke zaravni koji se stepenasto spušta prema polju, na nižim dijelovima zapadnih padina Liba te na blago položenim (nagib 2–5°) SZ padinama oblikovanim u stijenama krozne starosti na području kontaktu Ljubuše i krajnjega zapadnog dijela Vrana.

**Planarna zakrivljenost** odnosi se na zakrivljenost padine u sektori izohipse okomitoj na smjer najvećeg nagiba. Pozitivna vrijednost ukazuje na konvексni oblik padine, a negativna na konkavni, dok nulta vrijednost označava linearnu (pravocrtnu) padinu (Sl. 11.). Kada je zadani smjer okomit na smjer najvećeg nagiba (horizontalna sektori izohipse), tada se modelom zakrivljenosti padina mogu procijenjivati divergencija (konvексne, izbočene padine) odnosno konvergencija (konkavne, udubljene padine) hipotetskog otjecanja (a time i lokalne ocjeditosti ili vlaznosti tla na padini) (Antonić, 1996.). Konvergentno otjecanje povezano je s procesima akumulacije vode, tla ili detritusa, a divergentno otjecanje uz derazijske procese spiranja, puzanja, jaruženja i bujčenja.

Iz podataka o strukturi planarne zakrivljenosti (Tab. 5.) uočljiva je dominacija konveksnih i konkavnih padina u odnosu na pravocrtne, na razini cijelog područja, s dominacijom konveksnih (52,10%) u odnosu na konkavne padine (44,04%). Pravocrtne padine imaju mali udio, od samo 3,86%. To znači da je na razini canyon, along the fault line separating Tušnica and Jelovača, along the fault between north section of Vran and Ljubuša Mountain western slopes, and along the fault that curves northwest-southeast along the central Lib Mountain area.

Profile linear slopes are most frequent near the geologically new, Tertiary Tomislavgrad hills closer to the Polje at all the observed height levels i.e. they do not show a specific pattern of vertical occurrence (Fig. 10). They can also be found in the far southeast part of the Grabovica plateau, which gradually descends towards the Polje, on lower levels of Lib Mountain western slopes and the low-inclined (2-5°) northwestern slopes of Cretaceous period at the contact between Ljubuša and far west end of Vran Mountain.

**Planar curvature** denotes a slope’s curvature on the secant line perpendicular to direction of the greatest inclination. A positive value indicates a convex shape of the slope, while negative indicates a concave shape. A zero value indicates a linear slope (Fig. 11). If the given direction is perpendicular to the direction of the greatest inclination (the horizontal secant line of a contour line), then, using the slope curvature model, it is possible to evaluate divergence (convex slopes) or convergence (concave slopes) of a hypothetical water flow (and, by extension, local water flow features and soil humidity) (Antonić, 1996). Convergent flow is related to water, soil and detritus accumulation processes, while divergent flow is related to the processes of soil wash, creep, sinking and gully erosion.

From the data that refer to the planar curvature (Tab. 5) it is evident that convex and concave slopes dominate, when compared to linear ones, in all of the researched area. Convex slopes are predominant (52.10%), even compared to concave slopes (44.04%). Linear slopes make up a very small portion of only 3.86%. This means that
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Tablica 5. Tipovi i prostorni obuhvat planarne zakrivljenosti
Table 5 Different types and spatial coverage of planar curvature

| Padine          | Površina (m²) | Udio (%) |
|-----------------|---------------|----------|
| Konveksne       | 124412800,0   | 52,10    |
| Pravocrtne      | 9210400,0     | 3,86     |
| Konkavne        | 105179600,0   | 44,04    |
| Ukupno          | 238802800,0   | 100,00   |

| Slopes          | Area (m²)     | Coverage (%) |
|-----------------|---------------|--------------|
| Convex          | 124,412,800.0 | 52.10        |
| Linear          | 9,210,400.0   | 3.86         |
| Concave         | 105,179,600.0 | 44.04        |
| Total           | 238,802,800.0 | 100.00       |

cijelog područja prisutna dominacija divergentnog u odnosu na konvergentno otjecanje površinske vode odnosno denudacijskih procesa u odnosu na akumulacije.

Područja izraženog divergentnog otjecanja mogu se uočiti na karti planarne zakrivljenosti padina (Sl. 12.). Radi se uglavnom o vršnim dijelovima i područjima hrptova između jaruga na padinama planinskih masiva, na svim hipsometrijskim nivoima. Prostranije zone planarne konveksne zakrivljenosti osobito su istaknute na području Tomislavgradskog mladog terciarnog pobrđa i južnih padin Tušnice, što se može dovesti u vezu s njihovim litološkim sastavom. Naime radi se o konglomeratima, pješčenjacima i laporima, laporima s konglomeratima i laporovitim vapnenicima paleogenske i neogenske starosti, podložnim denudacijskim procesima. Također, prostranije zone ovoga tipa planarne zakrivljenosti nalaze se na području zapadnjak planine Lib, uz više dijelove padina krajnjeg SL dijela Grabovičke zaravni okrenutih prema Duvanjskom polju (na kojima prevladava kategorija nagiba od 32 do 55°), te na području Vran planine.

Na velikim dijelovima istraživanog područja zone konveksne i konkavne planarne zakrivljenosti nalaze se u izmjeni na malim udaljenostima, s približno jednakim omjerima. Osobito je to izraženo na područjima Grabovičke zaravni i dijelova Ljubuške bližih Duvanjskom polju (Sl. 12.).

Dominacija konkavne planarne zakrivljenosti karakteristična je za područje vapnenacke zaravni između centralnog grebena Liba i njegove SL padine the whole area is characterized by domination of divergent water flow and denudation processes.

Areas of pronounced divergent flow are noticeable on the planar curvature map (Fig. 12). This primarily refers to peaks and ridges between gullies on mountains slopes on all the observed height levels. Wider areas of planar convex curvature are especially pronounced around Tomislavgrad hills dating from Tertiary and southern slopes of Tušnica, which can be related to their lithological structure. In fact, in their base these areas consist of conglomerates, sandstone and marl, marl with conglomerates, and marl limestone from Paleogene and Neogene, which are more susceptible to denudation. Also, wider areas of this planar curvature type are found in western areas of Lib Mountain, in higher parts of far southeast slopes of the Grabovica plateau oriented towards the Duvanjsko polje (in which 32-55° inclination category prevails), and on Vran Mountain.

Interchanging zones of convex and concave planar curvature can be found in great portion of the researched area, with approximately the same ratios. This is especially evident on the Grabovica plateau and in parts of Ljubuša Mountain closer to Duvanjsko polje (Fig. 12).

Domination of concave slope curvature is characteristic for limestone plateau area between the Lib Mountain central ridge and its northeastern slope, and for the limestone plateau area in the eastern part of Ljubuša Mountain located farther away from Duvanjsko polje. The reason for this
Planar linear curvatures show similar spatial distribution as profile curvatures, i.e. they can be found in Tertiary areas of Tomislavgrad hills (primarily near the areas closer to Duvanjsko polje), in far southeast parts of Grabovica plateau, on lower levels of western Lib Mountain, and on northern slopes of western Vran Mountain, near the contact zone with Ljubuša (Fig. 12).
Diskusija

Morfometrijska analiza reljefa primijenjena u ovom radu uključila je korištenje različitih metoda za precizno računanje numericnih parametara reljefa istraživanog područja, što je omogućilo međusobnu korelaciju navedenih parametara, ali i korelaciju s kartom tektonskih jedinica i geološkom kartom. Cilj ovakvog pristupa je egzaktnija interpretacija morfometrijskih parametara reljefa kao indikatora značajki endogenih i egzogenih procesa na istraživanom području.

Na istraživanom području dominiraju nagibi padina manji od 2° kao posljedica dominacije pretežito zaravnjenog reljefa Duvanjskog polja. Manja izolirana područja ove kategorije javljaju se unutar rubnog planinskog okvira polja, na korozijama terasa, zaravnima, vršnim dijelovima planinskih hrtova i masiva, te ponikvama. Značajan je i udio kategorija nagiba od 5 do 12° i od 12 do 32°, koje se javljaju uglavnom na padinama planinskih masiva (osobito uz kontaktno dijelove s poljem). S porastom visine dolazi do većeg udjela kategorija od 12 do 32° i > 55°, koje se javljaju uglavnom na padinama planinskih masiva i debljini masiva, te ponikvama. Značajne su kategorije nagiba 5-12° i 12-32°, koje se javljaju uglavnom na padinama planinskih masiva i debljini masiva, te ponikvama.

Dominacija ekspozicija padina prema južnom kvadrantu (JZ, J, I, JI), zbog većih dnevnih i sezonskih temperature amplituda, upućuje na povoljne uvjete za nastanak i razvoj egzogeomorfoloških procesa na većem dijelu područja. Osim toga, dugotrajna dominacija sunčevog zračenja na južnoj ekspoziciji područja, koje se javlja uglavnom na padinama planinskih masiva i debljini masiva, te ponikvama, upućuje na neposredne i drugi posljedici egzogeomorfoloških procesa na južnoj ekspoziciji područja.

Značajne su kategorije nagiba 5-12° i 12-32°, koje se javljaju uglavnom na padinama planinskih masiva i debljini masiva, te ponikvama. Značajne su kategorije nagiba 5-12° i 12-32°, koje se javljaju uglavnom na padinama planinskih masiva i debljini masiva, te ponikvama. Značajne su kategorije nagiba 5-12° i 12-32°, koje se javljaju uglavnom na padinama planinskih masiva i debljini masiva, te ponikvama.

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parametra profilne zakrivljenosti s kartom nagiba, tektonskom i geološkom kartom. S druge strane, rubni planinski okvir polja u procesu je izdizanja (izraženija dominacija konveksnih padina u odnosu na konkavne u odnosu na prosjek cijelog područja). To vrijedi za Ljubušu, Grabovičku zaravan (s Midenom planinom), Tomislavgradsko pobrđe, Jelovača i zapadne padine Vrana. Dakle, radi se gotovo o cijelom planinskom okviru polja (osim Liba, Tušnice i Mesihovine). Općenito gledajući, značajke neotektonskih pokreta vrlo su složene te ih je potrebno detaljnije analizirati na razini manjih orografskih ili strukturnih jedinica.

Što se tiče značajki planarne zakrivljenosti, još je izraženija dominacija konveksnih u odnosu na konkavne padine, što upućuje na intenzivnije djelovanje egzogenih morfoloških destruktivnih procesa. Na taj način, veliki udjel dolomita (Tušnica i Vran) i lapora s konglomeratima (Tomislavgradsko pobrđe), veće nagibe i ekspozicije južnog kvadranta, to je potrebno analizirati na razini manjih orografskih ili strukturnih jedinica.

Zaključak

Primjenjivost morfometrijske analize provedene u ovom radu temelji se na njezinu sintetičkom karakteru, jer su svi morfometrijski, litološki i strukturni parametri, kao reprezentanti utjecaja endogenih i/ili egzogenih morfoloških procesa, dovedeni u međusobnu vezu. Na taj način moguće je izdvojiti područja različitih značajki endogenih i egzogenih morfoloških procesa, a korelacija s tektonskom i litološkom kartom omogućuje dodatnu verifikaciju utvrđenih činjenica vezanih uz značajke navedenih procesa. Na taj način moguće je procjena recentnog stanja dinamičke stabilnosti reljefa, što može biti od velike praktične važnosti gotovo za sve aspekte ljudske djelatnosti na istraživanom području.

Curvature with the inclination map, tectonic map and geological map. On the other hand, the Polje’s mountainous rim is in the process of upward movement (domination of convex slopes in relation the whole area’s average). This refers to Ljubuša Mountain, the Grabovica plateau (with Midena Mountain), Tomislavgrad hills, Jelovača and western Vran Mountain slopes. Evidently, this almost encompasses the entire mountainous rim except Lib, Tušnica and Mesihovina. Generally, characteristics of neo-tectonic movements are very complex and require a more detailed analysis on the level of smaller orographic or structural units.

As for planar curvature characteristics, domination of convex slopes is even more evident in comparison to concave ones, which indicates intensified activity of exogenous morphological destructive processes in comparison to accumulation processes. Areas with greater proportion of planar convex curvature are most prominent around Tomislavgrad Tertiary hills, Tušnica and Vran Mountain, which leads to conclusion that in those areas exogenous destructive processes are very prominent. This is further reinforced by the areas' lithological structure i.e. large proportion of dolomite (Tušnica and Vran) and marl conglomerates (Tomislavgrad hills), along with greater inclinations (Tušnica, Vran) and/or the southern quadrant aspect. Similar to profile curvature characteristics, the planar curvature is also rather complex in the entire researched area and requires further analysis and comparison at smaller orographic and structural units’ level.

Conclusion

Applicability of morphometric analysis used in this research is based on its synthetic character, since all the morphometric, lithological and structural parameters, as representatives of endogenous and exogenous morphological processes’ influences, have been mutually related. This enabled the identification of certain areas of various endogenous and exogenous morphological processes, while correlation with geological and lithological maps enabled additional verification of the results related to the aforementioned processes’ features. In this manner, it is possible to evaluate the recent condition of the relief’s dynamic stability, which can be of great practical importance for almost all aspects of anthropogenic activities in the researched area.
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