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Izvorni znanstveni članak

Features of Slope Inclination and Planar Curvatures of the broader Area of Duvanjsko polje

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ABSTRACT. In this paper, quantitative geomorphological features (slope inclinations, profile and planar curvature) of mountain rims of Duvanjsko polje were analyzed. Recent shape of this area is a consequence of series of natural and social impacts during relief genesis and evolution. The aims of this research are analysis of quantitative features of hillslope inclinations and curvatures of morphological units in wider Duvanjsko polje area, interpretation of results and synthesis, so more detailed insight in hillslope features and processes can be achieved and evaluation of nature of dominant geomorphological processes can be obtained. During this task, special attention was given to a detailed geomorphometric analysis in GIS environment based on a digital relief model. The analysis was conducted in several phases: 1. comparative analysis of hillslope characteristics based on morphological units, 2. comparative analysis of hillslope curvatures and 3. analysis of relationship between slope inclinations and curvature features. Synthesis included interpretation of obtained results in wider context of relationship between morphometric features and structural/lithological features of morphological units.

Keywords: broader area of Duvanjsko polje, morphological units, hillslope inclinations, profile and planar curvature, morphometry, GIS, DTM.

1. Introduction

This paper analyzes specific features of hillslopes of morphological units located on the broader area of Duvanjsko polje, with inclination >2°, i.e. the area of mountainous rim of Duvanjsko polje. The recent shape of slopes of this area is the

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consequence of effects of various natural and anthropogenic factors that occurred during the genesis and evolution of the terrain.

Aims of this research are the analysis of quantitative features of slopes and planar curvatures of morphological units of broader area of Duvanjsko polje, the interpretation and synthesis of results in order to achieve a more detailed insight into characteristics of slopes and slope-related processes on the researched area, but also to enable the estimation of characteristics of dominant geomorphological processes. Additionally, a special attention is given to a more detailed geomorphometrical analysis of morphological units of the broader area of Duvanjsko polje in GIS environment, based on the digital terrain model (DTM).

For the purposes of this research, a digital raster terrain model of of the broader area of Duvanjsko polje was made by automatic vectorization of isolines from topographic maps scaled 1:25 000. From that model, a series of data on slopes and curvatures were attained (both planar and profile curvatures). A detailed analysis of the available bibliography on structural and lithological features and the employment of GIS methods is also included, most notably the digital analysis of the terrain model (Franklin 1987, Dikau 1989, Jordan and Csillag 2001, Dikau et al. 2004, Ganas et al. 2005, Li et al. 2005, Smith and Clark 2005, Pike et al. 2009).

The analysis was carried out in a number of phases: 1. comparative analysis of slope inclinations with respect to morphological units, 2. comparative analysis of - features of planar curvature with respect to morphological units, 3. relation between slope inclination and features of curvatures of morphological units. The synthesis included interpretation of results in a broader context of relation between morphometrical features of slope inclination and planar curvature on one side and structural and lithological features of morphological units on the other side.

By application of quantitative and geomorphological approach within the analysis of slope features it is possible to analyze their connection to geological structure and content, as well as exogeomorphological factors (e.g. climate, pedology, vegetation etc.) and enable an estimation of stability, hence setting up a methodological framework that can be applied in practical purposes (construction, tourism, agriculture etc.). Most researches have shown that data on slope features and planar curvatures often indicate size, intensity and consequences of exogenous geomorphological processes within local context (Evans 1972, Evans 1980, Armstrong 1987, Zevenbergen and Thorne 1987, Parsons 1988, De Oliveira 1990, Evans and Cox 1999, Roering et al. 1999, Rieke-Zapp and Nearing 2005, Di Stefano et al. 2000, Lozić 2001, Pahernik 2007, Ohlmacher 2007), or endogenous (primarily neotectonical) morphostructural processes on a regional level (Thorne et al. 1987).

2. Researched area

Geotectonically speaking, the broader area of Duvanjsko polje is high karst or "cover of high karst" (Čičić 2002). The total researched area is 250.9 km^2. The oldest layers of this area are made up from limestones and dolomites from Jurassic period, while Cretaceous limestones, and dolomites to a lesser extent, are most widely spread.

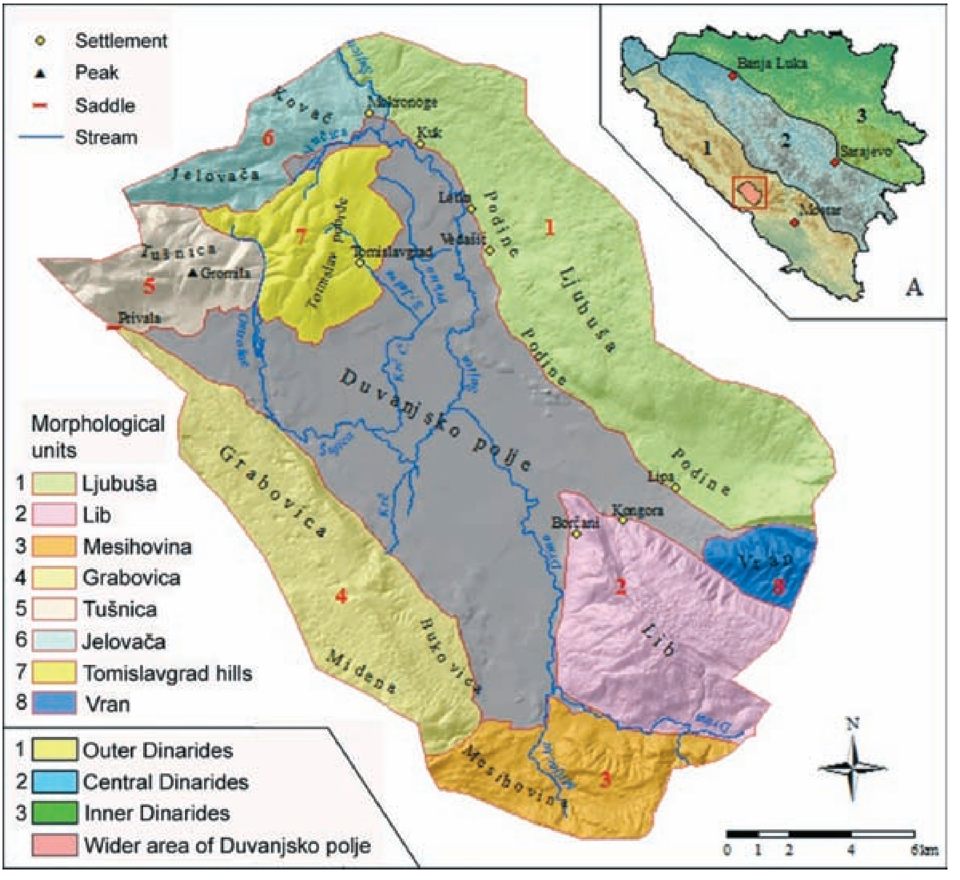

Fig. 1. *Geographical location of morphological units of broader Duvanjsko polje area.*

Newer layers are represented mostly by paleogenic limestone and clastite as well as lake sediments of Miocene. Structural units were shaped by the end of Paleogene, and were affected by significant vertical movement in Neogene, which caused a disturbance in the order of layers (Papeš 1985). Within the researched area eight morphological units were identified due to variable lithological content and structure, and in order to enable a more detailed analysis and comparison (Fig. 1).

In order to achieve a better understanding of causality between geological features and quantitative indicators of slope inclinations and curvatures, a short overview of basic geological features of morphological units is presented (Fig. 2).

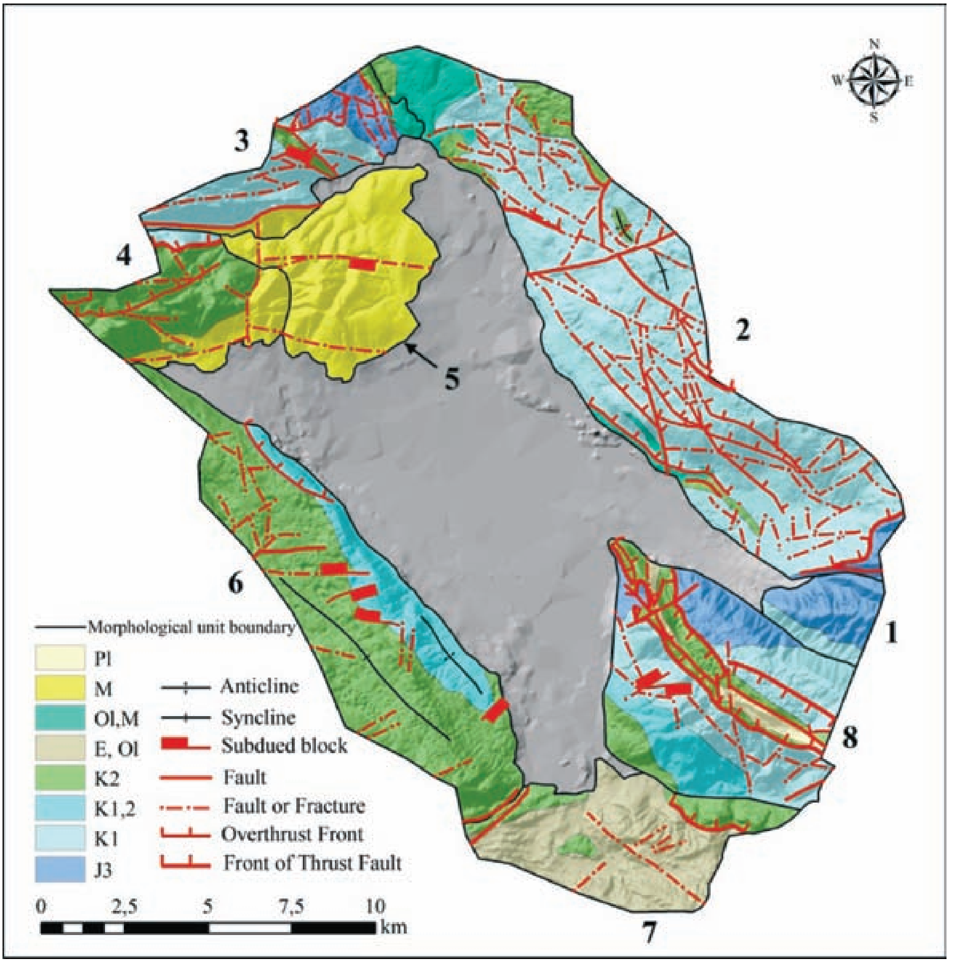

Fig. 2. *Geological map of the researched area, morphological units (1 = Vran, 2 = Ljubuša, 3 = Jelovača, 4 = Tušnica, 5 = Tomislavgrad hills, 6 = Grabovica, 7 = Mesihovina, 8 = Lib).*

2.1. Vran

The morphological unit of Vran mountain is the smallest in area, only 6.7 km^2. From the morphological unit of Lib Mountain to the south it is divided by Grla – Svinjača fault, while the fault located in a ravine from Podkose to Omrčenica creates the northern border towards the morphological unit of Ljubuša mountain. Vran Mountain stretches from east to west. This morphological unit is mostly made up from Malm limestone and dolomite, while the southern part is made up from limestones of late Cretaceous period.

2.2. Ljubuša

The morphological unit of Ljubuša Mountain rims Duvanjsko polje from east, from the Mokronoge to Lipa. The total area is 77.4 km^2. It stretches in direction from southwest to southeast, and near the village of Mandino selo it starts to curve and change direction to "Vran" type (W-E). The area of the morphological unit between Vedašić and Mandino Selo is characterized by numerous faults, overthrusts and crusts. Rock composition is mostly homogenous in form of sediments from early Cretaceous period. This is mostly the case of limestones, while dolomites make up a wider area only east of Vedašić. Limestones of late Cretaceous period are present only in the far northern rim of this unit. The most recent layers are those of Oligocene-Miocene conglomerates, which are present around Šujica canyon, near Mokronoge.

2.3. Jelovača

Šujica canyon in the east separated this unit from the unit of Ljubuša mountain. The morphological unit of Jelovača rims the Duvanjsko polje from the north. Jelovača stretches from east to west, which is caused by neotectonic movements that affected this area in Miocene period. In the eastern part of this unit, the most present rocks are Malm limestones and dolomites that shift into limestones of early Cretaceous period towards the west. Limestones of late Cretaceous period appear only partially, and mainly in the middle section of this unit. The most recent layers of sediments are Miocene marl, sands and conglomerates that show up in Vučipolje, which makes a triple boundary between this unit and the units of Tušnica and hills of Tomislavgrad. This morphological unit has the total area of 16.9 km^2.

2.4. Tušnica

The morphological unit of Tušnica Mountain is divided from Jelovača to the north by a fault stretching from Buhovo, across Vučipolje and further west. To the east, the border with Tomislavgrad hills stretches from Vučipolje along the line of Ostrožac stream to the village of Jošanica. To the southwest, a mountain pass Privala designates the border with Grabovica unit. Tušnica unit is made mostly out of sediments from late Cretaceous period, and, to a lesser extent, out of Miocene marl. Tušnica stretches from east to west, and its genesis is connected with neotectonic movements from late Miocene. The most recent layers are moraines near Vučipolje. This morphological unit has the total area of 17.8 km^2.

2.5. Tomislavgrad hills

Tomislavgrad hills are made completely out of marl that is lake sediment from Miocene. These layers have been washed away by rivers in some parts of Duvanjsko polje, as well as torrenting streams which flow toward the field or have been covered by more recent sediments. These sediments were elevated above the level of the field by neotectonic movements and make an appendix of Tušnica Mountain. Tomislavgrad hills have the total area of 21.8 km^2.

2.6. Grabovica

The morphological unit of Grabovica rims the Duvanjsko polje from the west and it is completely made out of limestone dating from the transition from early to late Cretaceous period. It is in fact a karst plain with a protruding anticline in its southern part, which is Midena Mountain. Its total area is 45.7 km^2.

2.7. Mesihovina

The morphological unit of Mesihovina includes the southern part of Duvanjsko polje. It is divided from the morphological unit of Grabovica to the west by a fault stretching from NE to SW. To the northeast, it is divided from the morphological unit of Lib by a narrow and short valley of the Studena stream. This morphological unit is mostly made out of Paleogenic clastite layers of conglomerates from middle Oligocene (E, O1). Layers of limestone (K2,3/2) appear at the transitions from Grabovica to Lib morphological unit, as well as Glavica area, which constitutes a tectonic window. It has a total area of 24.5 km^2.

2.8. Lib

The oldest sediments in the morphological unit of Lib are made out of limestone and dolomite from Jurassic period (J2,3/3). They appear in a narrow region between the rim of the field and the Lib Mountain ledge, near the village of Borčani, as well as NE side of Lib Mountain, where they cover the older Cretaceous sediments from NE direction. They transition into sediments from early Cretaceous period towards south and southeast, which are mostly made out of gray dolomite rocks, interchanging with limestone. Stretching from Omolje in the direction of south-southeast, sediments transition to gray limestones of Albian-Cenomanian period. Sediments from late Cretaceous period can be found on several locations (e.g. the area of Lib Mountain edge). Northeastern and southwestern border of these sediments are characterized by overthrusts, and between two of such thrusts the ravine of Kongora – Žabljak is located. The most recent sediments of Lib unit are made out of marl and clay, in the area of Kosovac. Its total area is 39.9 km^2.

3. Methodology

Digital terrain model is used to describe geomorphological, hidrological and biological processes on the surface of Earth (Moore et al. 1991, Dietrich et al. 1993). The process that describes terrain in a quantitative manner is known as digital terrain analysis (DTA). DTA is a totality of techniques used for topographic analysis and performance of various terrain-related parameters (morphometric, hidrological, climatological) from a digital terrain model, or DTM (Hengl et al. 2003). Slope inclination and curvature are local terrain parameters (Olaya 2009). Slope inclination is a first derivative of surface, while curvature represents a second derivative (Moore et al. 1991, Zeverbergen and Thorne 1987). For the purposes of this paper, DTM was performed by methods of vectorizing contour lines from topographic maps. Methods can be identified in regards to precision, density and price of collecting data (Weibel and Heller 1991, Hengl et al. 2003).

The process of employing DTM took several steps (Fig. 3): 1) analysis of topographic maps, 2) georeferencing and transformation, 3) grouping colors, 4) defining contour lines from topographic maps, 5) semiautomatic and manual vectorization, 6) applying attributes (height data), 7) choosing interpolation method, 8) calculating and choosing spatial resolution.

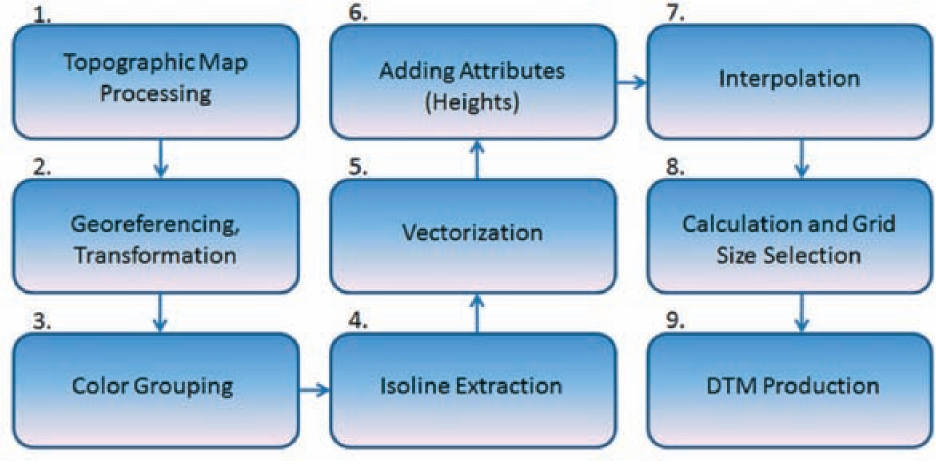

Fig. 3. *The scheme of DMR making.*

These factors influenced output results of DTM: vertical terrain dissection, interpolation method, methods of DTM making, pixel size, vertical precision or resolution and types of algorithms.

Generally speaking, the researched area is extremely vertically dissected, which is accented by a vertical difference of 839 meters.

A significant role in gathering high quality output results was that of interpolation method. Interpolation is a method of calculating a new, unknown value between two or more known values of a certain function. Its value never exceeds the value of known function values. There are 42 methods of interpolation (Lee and Heap 2008), which are divided into three groups: 1) non-geostatistical (TIN, TSA, etc.), 2) geostatistical (univariant and multivariant), various Kriging and Cokriging methods, 3) combined methods (TSA and Kriging, Linear mixed model etc.). This research employs one of the more frequent methods: triangulation method, which generates an irregular grid based on the dispersion of points by Delaunay triangulation method.

The method of vectorization of contour lines from topographic maps is one of the three methods for gathering data for DTM (Weibel and Heller 1991). It was chosen for two reasons: a) the availability of more precise data – DTM is limited in that respect, b) vertical precision – this specific DTM employs precision of 2 meters (Ackermann 1994). The available DTM (SRTM, EROS, ASTER) were made by method of radar recording which employs a vertical precision within 9 to 25 meters, depending on vegetation (Goncalves and Oliveira 2004, Huggel et al.

2008). The possibility of application of geomorphological analysis from such DMR is limited to broader areas of research. Considering the density of contours, GIS software optimized the size of pixels to 26.98. Due to easier manipulation of data, pixel size was rounded at 25*25 meters.

There is a greater number of mathematical algorithms for calculating slope inclination and curvatures (Travis et al. 1975, Horn 1981, Heerdegen and Beran 1982, Zeverbergen and Thorne 1987, Hickey et al. 1994, Tarboton 1997), all of which affect the precision of output data (García Rodriguez and Giménez Suárez 2010). Methods and algorithms that were used were integrated in *ArcInfo* program. The principle of calculating slope inclination is such that the software, using 3*3 square method (Fig. 4), calculates the maximum rate of change in the value of heights from the central cell towards the surrounding neighboring cells (Fig. 5) (Burrough and McDonell 1998).

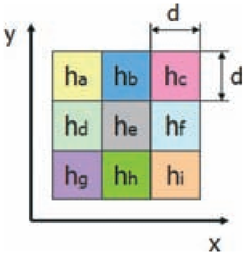

Fig. 4. *3*3 pixel method.*

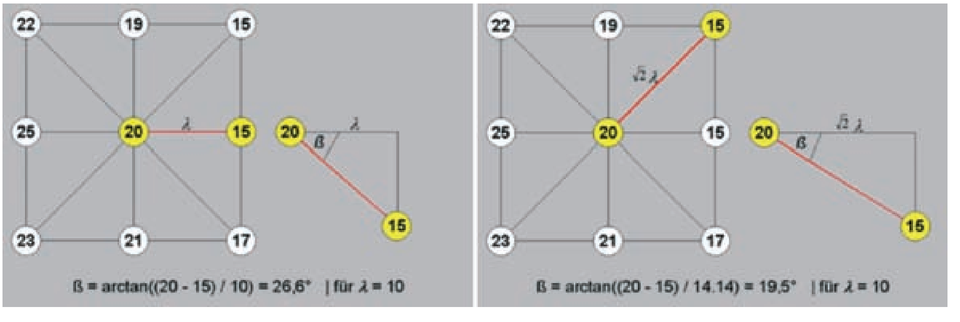

Fig. 5. *The greatest slope in 3*3 pixel environment.*

The grid made by cells of equal dimensions was flattened along the geographical axis *X* (west – east), and *Y* (north – south) (Fig. 1).

The rate of change in x-direction is calculated by the following algorithm:

$$h_x = ((h_c + 2h_f + h_i) - (h_a + 2h_d + h_g) / (8 * d).$$

The rate of change in y-direction is calculated by the following algorithm:

$$h_y = ((h_g + 2h_h + h_i) - (h_a + 2h_b + h_c) / (8 * d).$$

By calculating the rate of change in both x and y directions, slope inclination is then calculated by the method of border difference:

$$N = \sqrt{h_x^2 + h_y^2}$$

$$N(°) = ATAN\ (N).$$

Slope inclination by digital terrain model of grid structure si calculated as second derivative that describes the rate of change of the first derivative in x and y directions (Pahernik 2007). It is calculated according to the following formula:

$$h_{xx} = (h_f - 2h_e + h_d) / h^2$$

$$h_{yy} = (h_b - 2h_e + h_h) / h^2.$$

Two types of curvatures are analyzed and calculated in this paper: profile and planar. Profile curvature (Prof(z)) is the curvature of slope in the direction of the greatest inclination (Fig. 6):

$$Prof(z) = h_{xx}\, h_x^{\ 2} + 2h_{xy}\, h_x\, h_y + h_{yy}\, h_y^{\ 2} / pq^{2/3}.$$

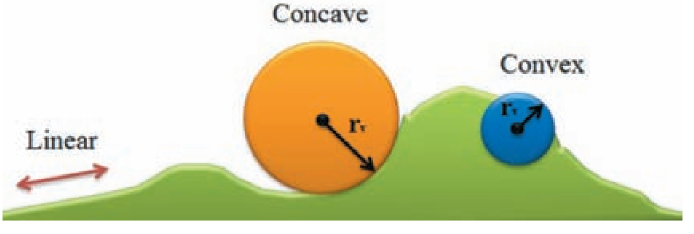

Fig. 6. *Profile curvature.*

If it is greater than zero, the function is convex, and, if it is lower than zero, the function is concave. Points in which the function shifts from concave into convex form, and vice versa, are called inflexion points.

Planar curvature is the curvature of hillslope in the secant line perpendicular to the direction of the greatest slope inclination (Pahernik 2007). It can be described as the curvature of hypothetical iso-lines that pass through pixels (Fig. 7). It is calculated according to the following formula:

$$Plan(z) = h_{xx}\, h_y^{\ 2} + 2h_{xy}\, h_x\, h_y + h_{yy}\, h_x^{\ 2} / pq^{2/3}.$$

where:

$$h_{xy} = - h_a + h_c + h_g - h_i / 4h^2$$

$$p = h_x^{\ 2} + h_y^{\ 2}$$

$$q = p + 1.$$

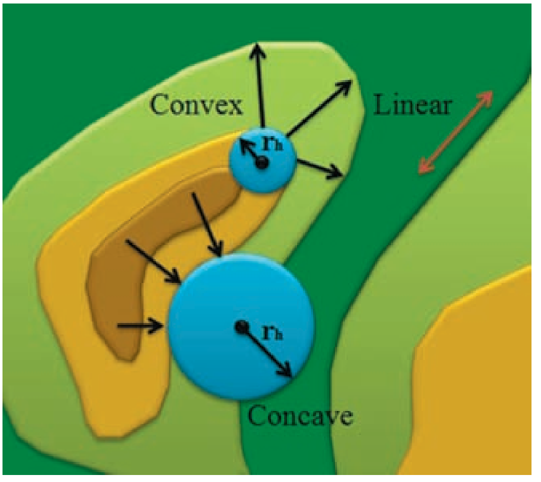

Fig. 7. *Planar curvature.*

4. Results

4.1. The structure and spatial distribution of slope inclination with regards to morphological units

From various data on structure and spatial distribution of hill side slopes in regards to morphological units (Fig. 8 and 9) it is noticeable that there are significant differences between individual morphological units. Inclinations of category 0–2° are generally rare (1.25–14.55%). These categories are more frequent in areas of morphological units of Grabovica, Mesihovina, Ljubuša and Tomislavgrad hills (8.18–14.55%). Main reasons are: a) the fact that some of these morphological units (Ljubuša and Grabovica) feature a great deal of areas that are based on limestone rocks and were reshaped by a long process of corrosion on a karst plain, which itself has interchangeable concave (karst dolines, uvalas, collapsed dolines) and convex shapes (heights or smaller areas between karst depressions); and b) on other morphological units (Tomislavgrad hills and Mesihovina) soften Tertiary sediments (marl) are most prominent, and since they are very susceptible to denudation and sedimentation of colluvial and diluvial material, the lower parts of this area (especially the trasition towards Duvanjsko polje) feature smaller slope inclinations.

Inclination category of 2–5° is the most prominent on areas of the same morphological units as the previous one. The reasons for that are basically the same as for the previous category, but the intensity of various sorts of morphological processes is stronger. That means that there have been more intense karst processes in areas of Ljubuša and Grabovica which feature slopes of this category, which has resulted in greater differences between concave and convex shapes. This has probably been enhanced by tectonics, i.e. the existence of several smaller faults and other structural discontinuities that are important for local terrain, and which coincide with areas of this category (Fig. 2 and 9). In areas of Tomislavgrad hills and Mesihovina, as well as those of previous category, due to a different lithological structure, there are cases of different geomorphological processes, i.e. more intense denudation and sedimentation of hillslope material, mostly at lower levels of hill sides.

Categories of inclination of 5–12° is the most dominant (relative to other categories) in areas of morphological units of Ljubuša and Tomislavgrad hills (48.67 and 42.83%), Grabovica, Mesihovina and Jelovača (39.09, 33.15 and 32.77%) (Fig. 8). This category also features the duality of geomorphological processes, depending on its lithological structure. The difference is that those areas where limestone dominates (Ljubuša, Grabovica) no longer feature mostly flat surface, but greater number of homogenous surfaces of developed limestone hillslopes and heights (of larger dimensions), on which a combination of surface watercourses and swallow-holes is present, in addition to a significant effect of tectonics (main and auxiliary faults and other structural discontinuities). All of this, combined with the effects of exposition, has an effect on vegetation characteristics and agricultural land types.

Categories of inclination of 12–32° are most frequent in areas of morphological units of Tušnica and Vran (64.64 and 63.70%), Lib and Jelovača (55.53% and 51.05%), and Mesihovina (37.62%) (Fig. 8). Other morphological units feature these categories to a much lesser degree, especially in relation to category of 5–12° (Fig. 8). Hillslopes within this category are dominant on peripheral sides of lime-

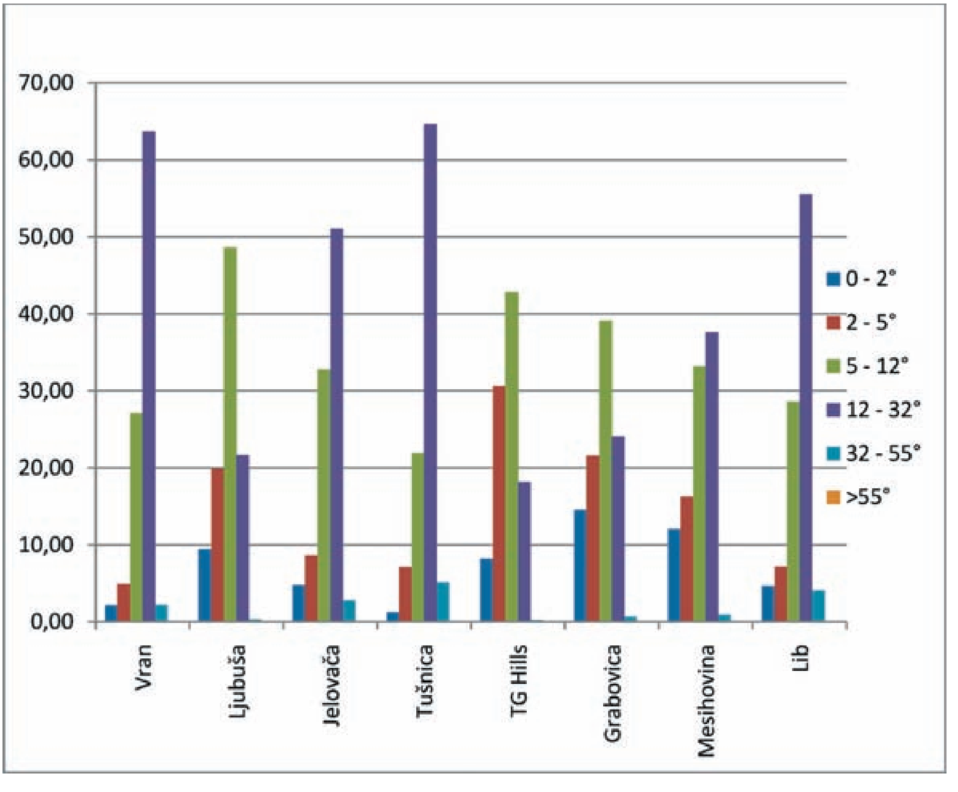

Fig. 8. *Structure of hillslopes in morphological units.*

stone flats (e.g. NE slope of Grabovica, which borders Duvanjsko polje by a steep slope, Fig. 9), sides of deep ravines and/or river or brook basins (e.g. a grid of ravines, brook and river basins of Tušnica and Mesihovina; peripheral sides of Šujica canyon in the bordering area between morphological units of Jelovača and Ljubuša), as well as slopes in higher parts of the aforementioned morphological units (Tušnica, Jelovača, highest parts of Lib). Occasionally, they can be found at lower levels of hillslopes, especially on those areas which are preconditioned to tectonic dislocations (e.g. lower parts of NE hillslope of Lib, near the fault on the contact area of Lib and SW hillslope of Vran Mountain, Fig. 2 and 9).

Slope inclinations of category 32–55° are present by a very small ratio and are mostly present within morphological units of Tušnica and Lib (5.10% and 4.06%) (Fig. 8). The main reason for that are morphological and morphostructural characteristics of these two morphological units, i.e. a greater proportion of areas of high altitude, significant terrain dynamics and frequent tectonic dislocations (faults, overthrusts and crusts) (Fig. 2 and 9).

Slope inclinations of >55° are present by an extremely low ratio, only appearing in the morphological unit of Lib, near the tectonically preconditioned steep hill sides of its central ledge.

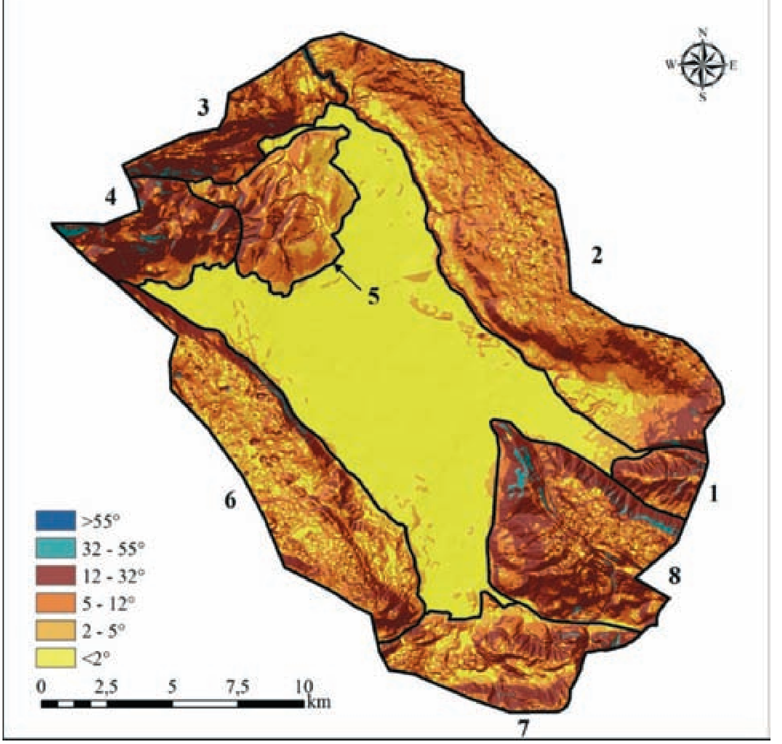

Fig. 9. *Spatial distribution of hillslopes in morphological units (1 = Vran, 2 = Ljubuša, 3 = Jelovača, 4 = Tušnica, 5 = Tomislavgrad hills, 6 = Grabovica, 7 = Mesihovina, 8 = Lib).*

4.2. The structure and spatial distribution of slope curvature with regards to morphological units

The notion of slope curvature refers to its geometric shape. The shape of the slope is a result of denudation (sheet washing, soil creeping, flowing, dispersion and collapsing) and accumulation, which are caused by endogenous and exogenous geomorphological factors.

The differentiation between concave, convex and straight slopes, made by Savigear (1952, 1956) and further developed by Young (1964, 1971), is still the basis of slope shape analysis.

Convex slopes (or parts of slopes) are indicators of positive tectonic movements (uplift) connected with domination of denudational processes in which the intensity increases with the increase of slope inclination. Straight or linear slopes (or parts of them) point to spatially balanced tectonic and denudational conditions which cause uniform movement of slope material down the slope, and, in a long-term sense, cause parallel transgression of slope caused by denudation. Concave slopes (or parts of them) are indicators of negative tectonic movements (lowering) connected with an increased amount of accumulation and sedimentation of slope material (Dikau et al. 2004).

4.2.1. Profile curvature of hillslopes

From the collected data on structure and spatial distribution of profile curvature on the researched area (Fig. 10), it is visible that convex and concave hillslopes are the most dominant.

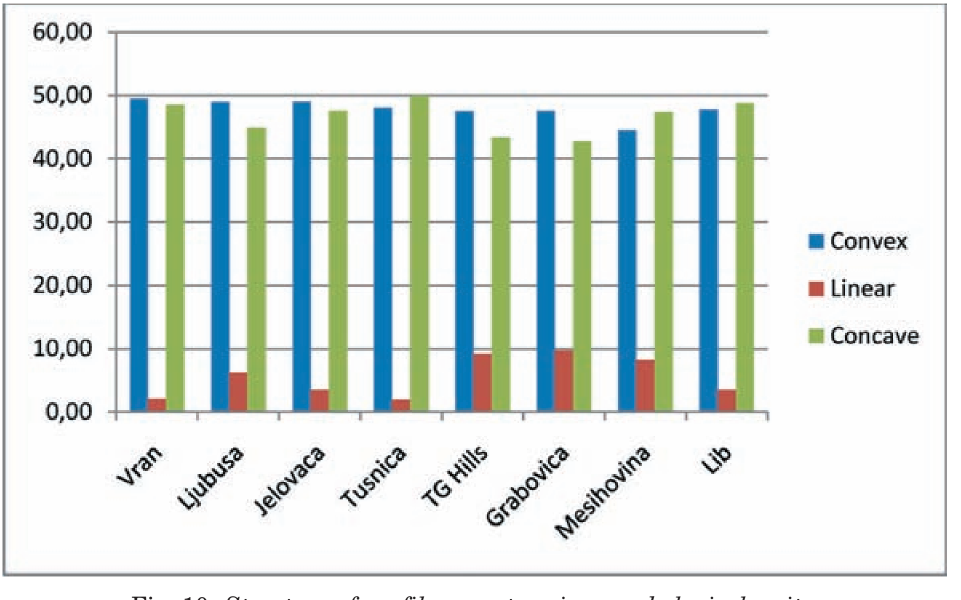

Fig. 10. *Structure of profile curvature in morphological units.*

Between individual morphological units there is no significant difference in the proportion of convex and concave slopes, in contrast to linear slopes, which show a greater degree of variability.

Linear slopes are the most frequent within the morphological unit of Tomislavgrad hills (5.6%). By comparison of spatial distribution of slopes with profile curvature (Fig. 11) and geological map (Fig. 2), a certain analogy is visible between the direction of convex and concave slopes on one side and the direction of anticlines, synclines, fault lines and fronts of overthrusts and crusts. This confirms the assumption about profile curvature as a reliable indicator of directions of tectonic movements (whether positive or negative). Areas with linear profile slopes are most often outside of tectonically active zones (faults), or near

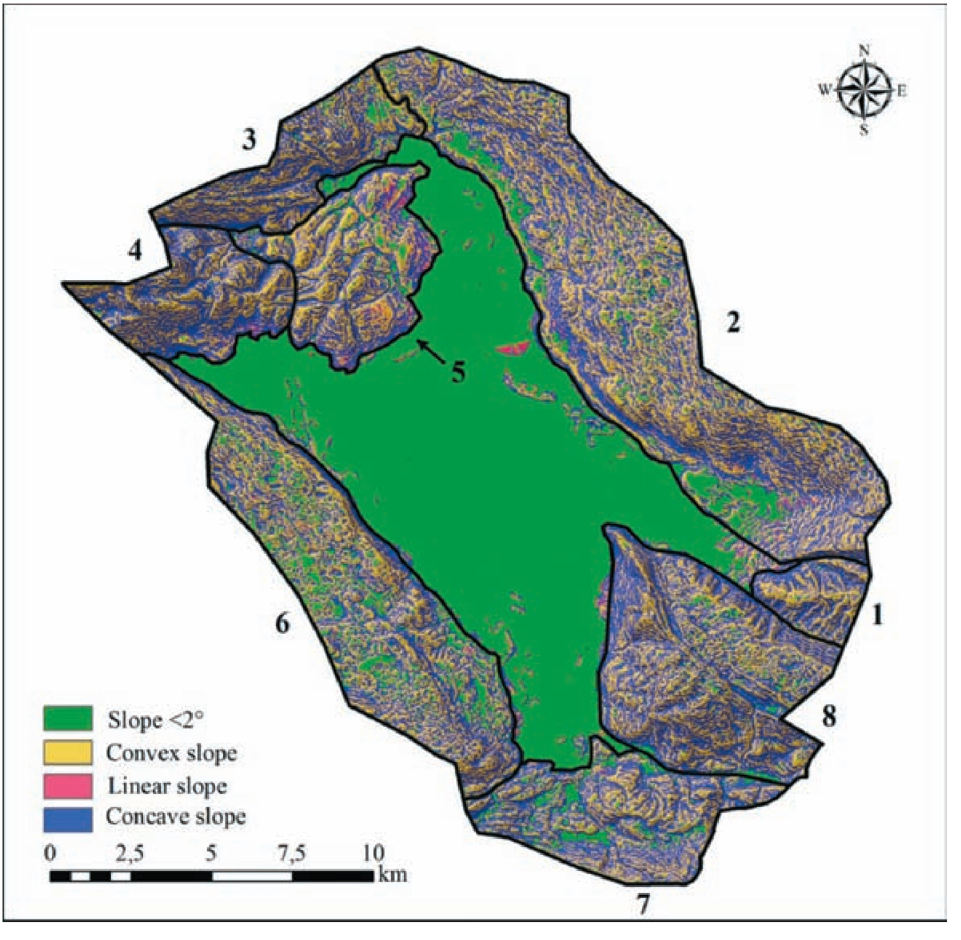

Fig. 11. *Spatial distribution of profile curvature in morphological units (1 = Vran, 2 = Ljubuša, 3 = Jelovača, 4 = Tušnica, 5 = Tomislavgrad hills, 6 = Grabovica, 7 = Mesihovina, 8 = Lib).*

those faults which have a less accented activity, i.e. which do not feature any major dislocations.

4.2.2. Planar curvature of hillslopes

Planar curvature structure is similar to that of profile curvature, meaning there is a certain degree of domination of convex and concave slopes, although the differences between their respective proportions are more accented within the individual morphological units (Fig. 12). Those differences primarily become notable in morphological units of Tomislavgrad hills, Vran, Ljubuša, Tušnica and Jelovača, where the domination of convex curvatures in comparison with concave ones is more apparent (Fig. 12 and 13). This type of situation hints at a relatively greater importance of exogenous geomorphological processes of denudation than those of accumulation, as well as combined effects of endogenous and exogenous processes on the morphological shaping of the terrain. This means that the process of denudation on those morphological units, which feature the most significant differences, is additionally enhanced in certain areas by positive tectonic movements.

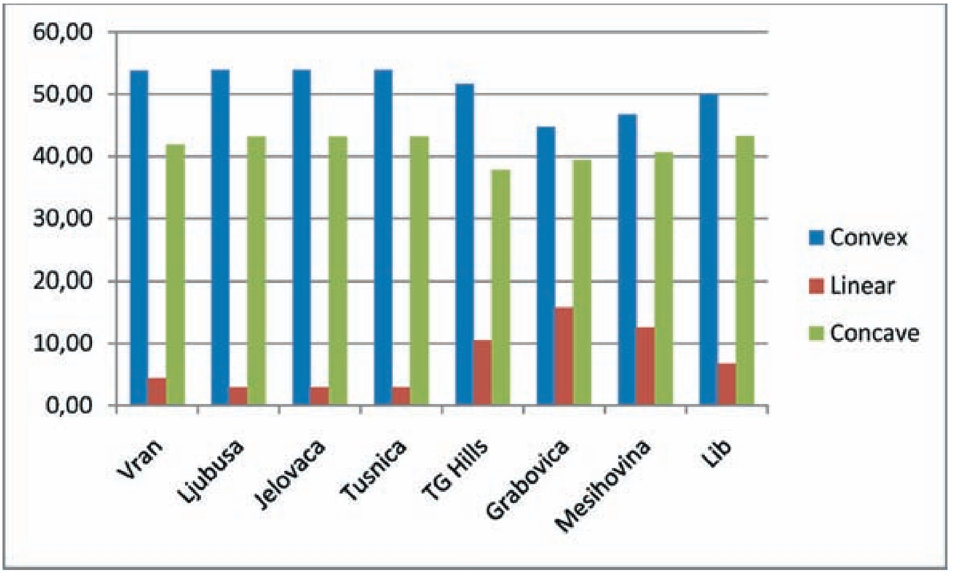

Fig. 12. *Structure of planar curvature in morphological units.*

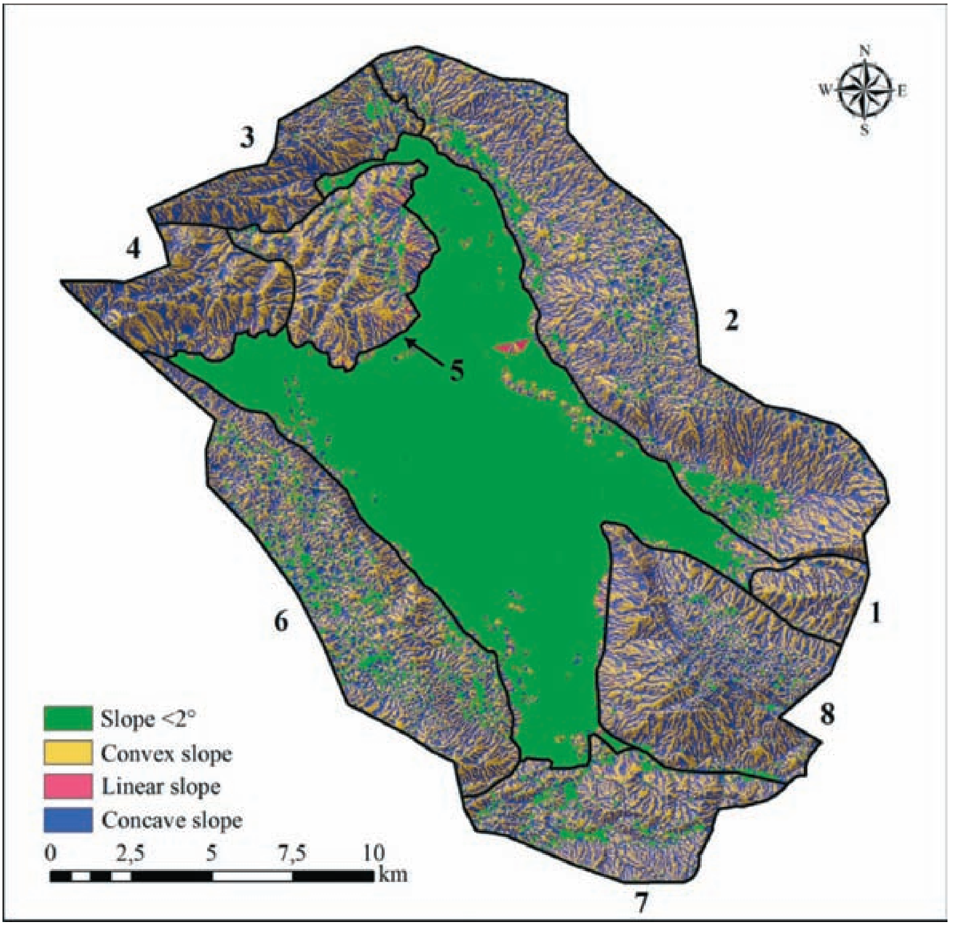

Fig. 13. *Spatial distribution of planar curvature in morphological units (1 = Vran, 2 = Ljubuša, 3 = Jelovača, 4 = Tušnica, 5 = Tomislavgrad hills, 6 = Grabovica, 7 = Mesihovina, 8 = Lib).*

4.2.3. Relation between types of profile and planar curvature of hillslopes

By analysis of the relation between profile and planar convex slopes of morphological units of the researched area it was concluded that there is no significant correlation between profile and planar convex and concave curvature, which is consistent with previous researches (Armstrong 1987, Parsons 1988). The coefficient of correlation between profile and planar convex curvature on the researched area is 0.13 (Fig. 14). Even less notable is the relation between profile and planar concave slopes (correlation coefficient is 0.04, Fig. 15). In contrast, the relation between profile and planar linear slopes show a significant positive relation (correlation coefficient is 0.83, Fig. 16), which is a result of nearly identical spatial distribution (Fig. 11 and 13).

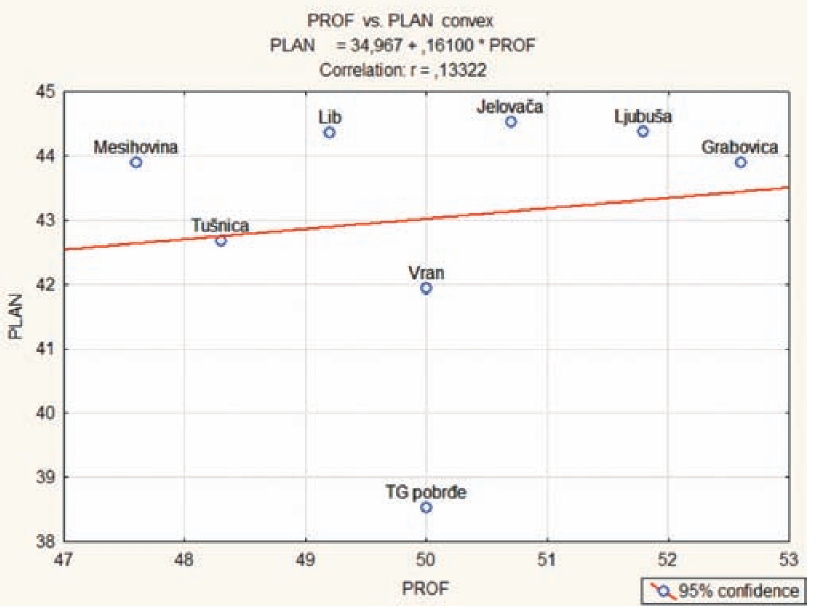

Fig. 14. *Relation between profile and planar convex curvature of slopes.*

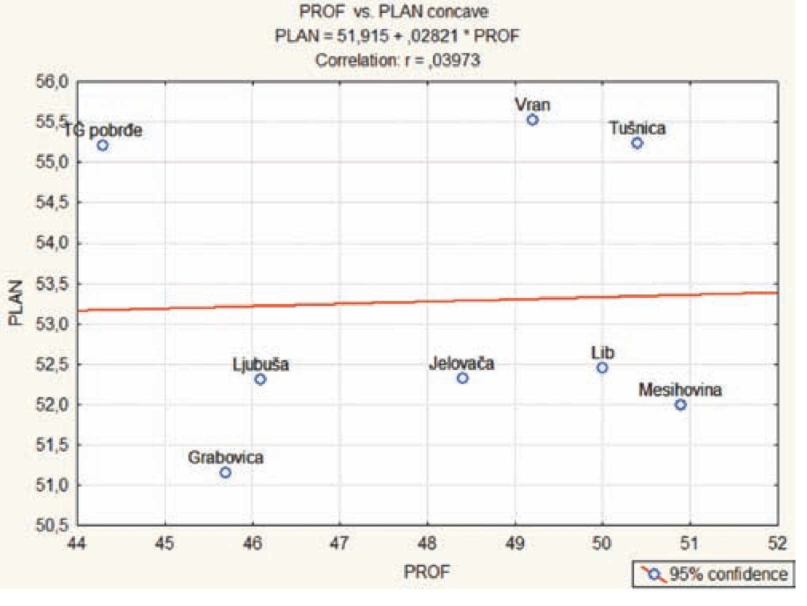

Fig. 15. *Relation between profile and planar concave curvature of slopes.*

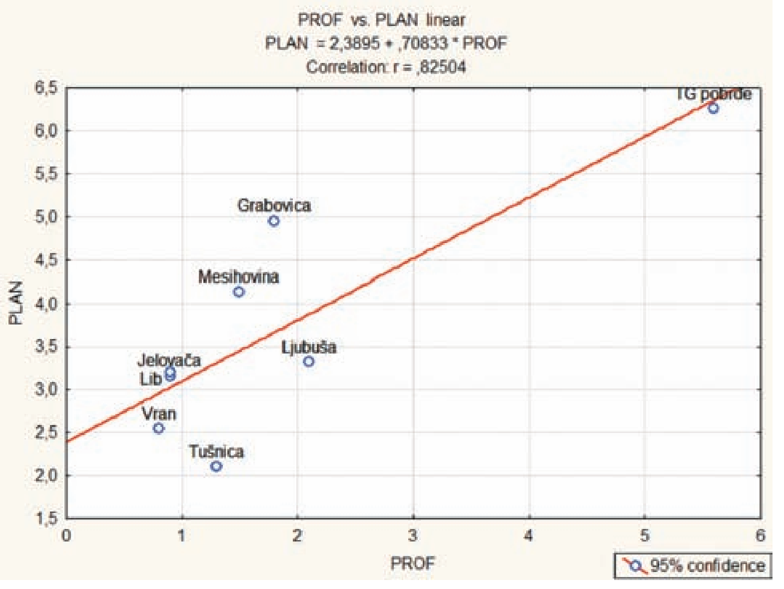

Fig. 16. *Relation between profile and planar linear curvature of slopes.*

4.3. Comparative analysis of the relation between slope inclination and profile and planar curvature

4.3.1. Relation between slope inclination and types of profile curvature

4.3.1.1. Relation between slope inclination and profile convex curvature

Based on data on the relation between slope categories and slopes with planar convex curvature in morphological units (Fig. 17), it is evident that there is an asymmetric distribution, i.e. domination of slope category 12–32° or 5–12° within the whole system. If the relation between slope inclination and profile convex curvature is observed with regard to morphological units, domination of slope category 12–32° is the most evident in units of Vran, Jelovača, Tušnica, Mesihovina and Lib. Considering the level of that relation, within those five morphological units the most prominent are Vran Vran (32.92%), Tušnica (32.40%) and, somewhat less prominent, Lib (27.73%).

Within the remaining three units, the significance of slope category of 12–32° is much less evident, i.e. slope categories of 5–12° are the most dominant (Ljubuša 25.32%, Tomislavgrad hills 22.29% and Grabovica 20.85%). Portions of other slope categories are much lower, with the category of 2–5° somewhat prominent within the morphological unit of Tomislavgrad hills (12.84%).

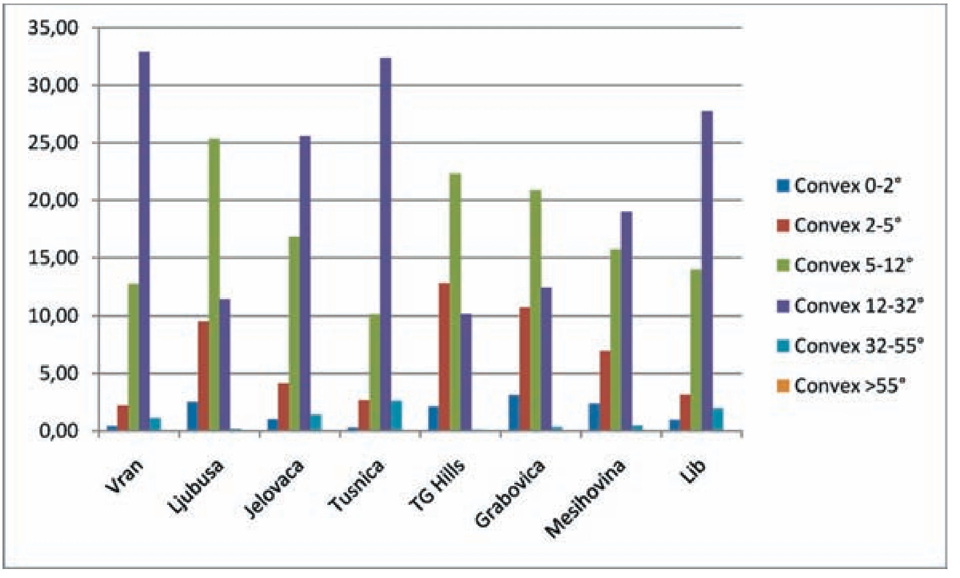

Fig. 17. *Relation between various slope categories and profile convex curvature.*

4.3.1.2. Relation between slope inclination and profile concave curvature

The relation between categories of slope inclination and profile concave curvature shows similar characteristics as the relation between inclination and profile convex curvature (asymmetry of distribution, i.e. domination of inclination category 12–32° and 5–12°), although, at the level of morphological units, there are evident differences (Fig. 18). They

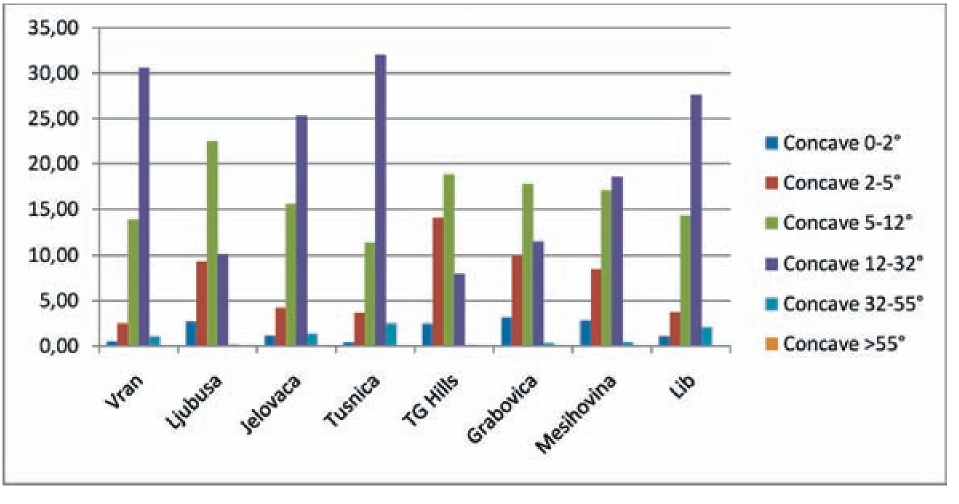

Fig. 18. *Relation between slopes of various categories of inclinaton and profile concave curvature.*

primarily refer to the hierarchy of distribution of slope category of 12–32°. Although the same morphological units seem to dominate, similar to convex curvature, their distribution according to the level of relation is somewhat different. The most dominant morphological unit is Tušnica (32.03%), followed by Vran (30.6%) and Lib (27.64%).

The portion of category of 5–12° within few morphological units is more significant than that of category 12–32°. This primarily refers to units of Ljubuša (22.48%), Tomislavgrad hills (18.85%) and Grabovica (17.8%), with the distribution nearly identical to that of convex curvature.

Portions of other categories of slope inclination are much smaller, with the category of 2–5° being somewhat prominent within Tomislavgrad hills (14.04%).

4.3.1.3. Relation between slope inclination and profile linear curvature

The structure of the relation between categories of slope inclination and profile linear curvature shows an extremely asymmetric distribution (Fig. 19), i.e. the greatest portion of its value is concentrated within the category of 0–2°. Areas of profile linear curvature are characteristic in morphological units of Grabovica (8.3%), Mesihovina (6.94%) and Ljubuša (4.23%). Grabovica and Ljubuša, in particular, feature exquisite instances of profile linear slopes with inclinations up to 2°, which can be found in on parts of corrosion terrace of Podine (Ljubuša) and flats on higher altitudes somewhat farther away from Duvanjsko polje (Grabovica and Ljubuša) (Fig. 11).

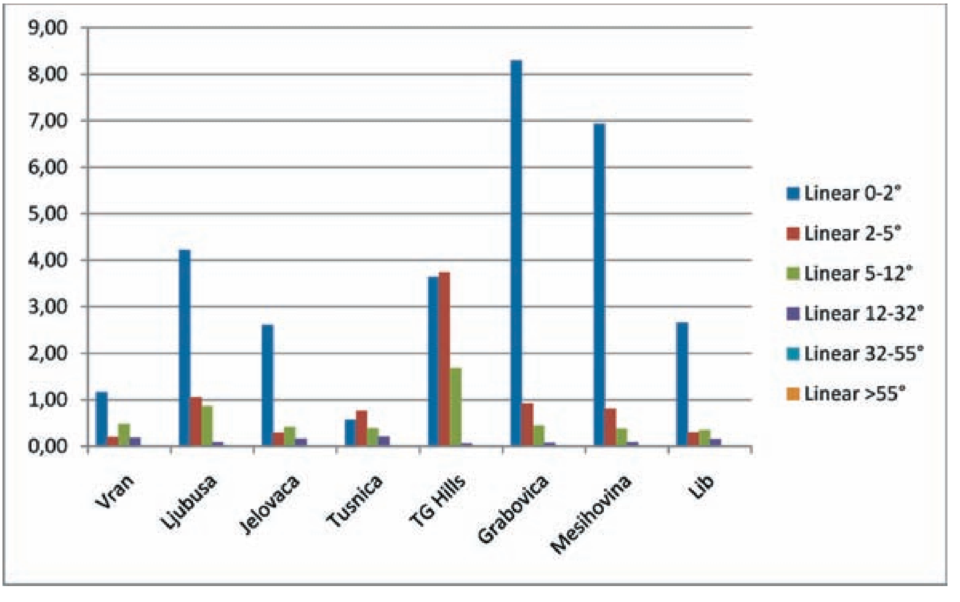

Fig. 19. *Relation between various categories of slope inclination and profile linear curvature.*

4.3.2. Relation between slope inclination and types of planar curvature

4.3.2.1. Relation between slope inclination and planar convex curvature

From the data regarding the relation between slope inclination categories and planar convex curvature in morphological units (Fig. 20), it is visible that, similar to profile convex curvature, there seems to be a case of asymmetrical distribution, i.e. domination of category of 12–32° and 5–12°. If the relation between slope inclination and profile convex curvature is considered with regard to morphological units, then the case of significant domination of category of 12–32° is notable in units of Vran (36.21%), Tušnica (36.47%) and Lib (30.1%). In a relatively smaller portion, the domination is present in Jelovača (26.79%) and Mesihovina (20.4%). Within the other units the portion of this category is significantly less prominent, someplace even less than 5–12°.

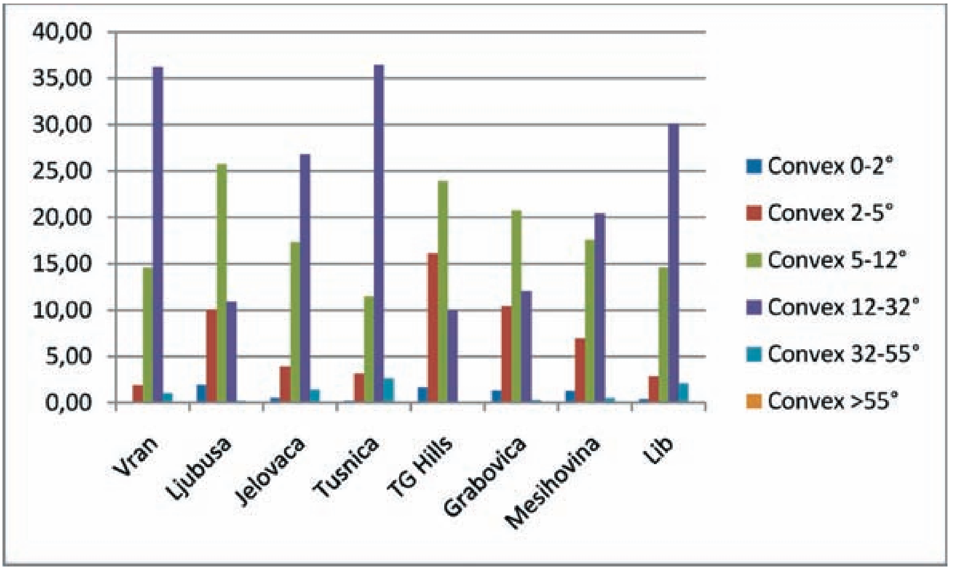

Fig. 20. *Relation of various categories of slope inclinations and planar convex curvature.*

Within the remaining three morphological units, the importance of inclination category of 12–32° is less prominent, i.e. what dominates are categories of 5–12° (Ljubuša 25.74%, Tomislavgrad hills 23.89% and Grabovica 20.72%). Portions of other categories are much lower, with the category of 2–5° being somewhat more frequent in the morphological unit of Tomislavgrad hills (16.08%). Inclination category of 5–12° is dominant in units of Ljubuša (25.74%), Tomislavgrad hills (23.89%) and Grabovica (20.72%).

4.3.2.2. Relation between slope inclination and planar concave curvature

Relation between categories of slope inclination and planar concave curvature at the level of the entire system shows similar features as the relation involving planar convex curvature (asymmetrical distribution, i.e. domination of inclination category of 12–32° and 5–12°), although, at the level of morphological units, there are differences (Fig. 21). This primarily refers to the hierarchy of distribution of slope inclination category of 12–32°; although, similar to convex curvature, same morphological units dominate, their hierarchy is somewhat different. The most dominant unit is Tušnica (27.68%), followed by Vran (27.11%), Lib (24.98%) and Jelovača (23.7%).

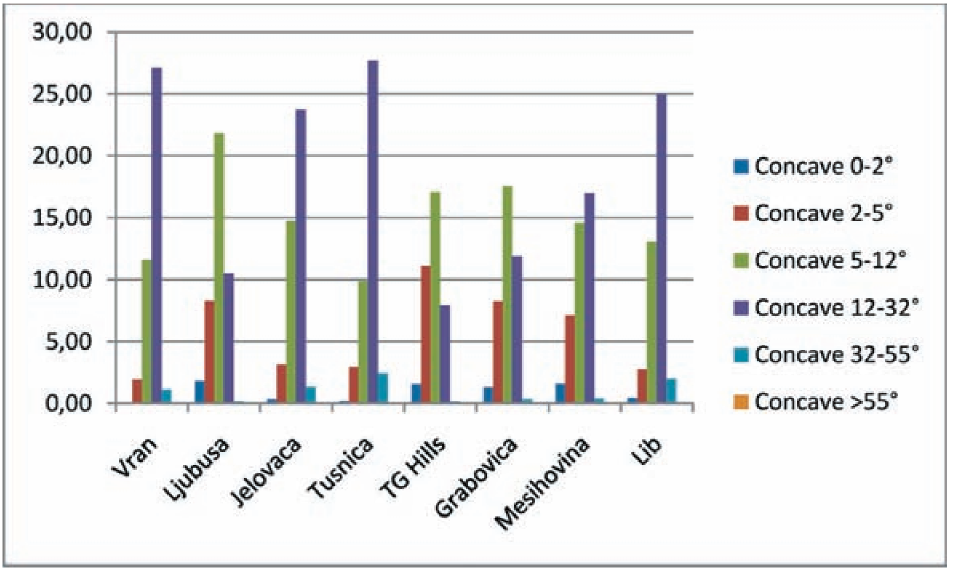

Fig. 21. *Relation between slope inclination and planar concave curvature.*

Morphological units with feature the portion of category of 5–12° greater than that of 12–32° are Ljubuša (21.8%), Grabovica (17.53%) and Tomislavgrad hills (17.07%), with the different hierarchy than that of convex curvature.

Portions of other categories are significantly lower, the only exception being the category of 2–5° which is somewhat prominent in Tomislavgrad hills (11.09%).

4.3.2.3. Relation between slope inclination and planar linear curvature

The structure of relation between categories of slope inclination and planar linear curvature in morphological units shows, similar to profile linear curvature, extremely asymmetric distribution (Fig. 22), i.e. the greatest portion of values is concentrated within the category of 0–2°. The greater portion of slopes with profile linear curvature is characteristic in morphological units of Grabovica (11.91%), Mesihovina (9.21%) and Ljubuša (5.71%). Notable is the fact that, in all the cases, portions of the category of 0–2° are greater than in the examples of profile linear curvature, which further adds to the fact that planar curvature is a better indicator of exogeomorphological forms and processes; specifically, this applies to concave terrain forms (bottoms of ravines, valleys, karst sinkholes, basins etc.) which

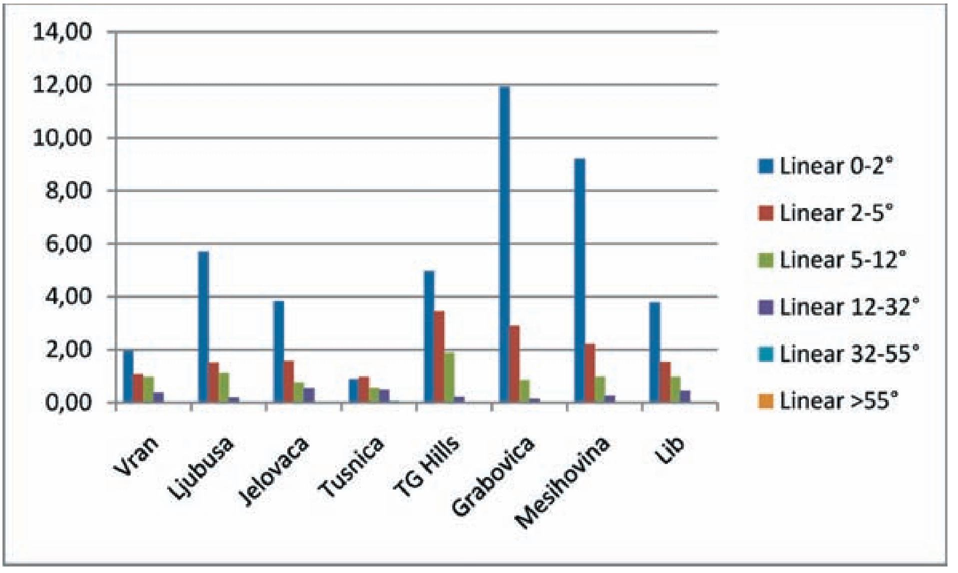

Fig. 22. *Relation between slope inclination and planar linear curvature.*

are analyzed with significantly lower level of precision if registered by profile curvature.

5. Discussion

Based on the analysis of the structure of slope inclination, profile and planar curvatures, and the relation between inclination categories and types of curvatures, the following points have been concluded:

- From the data on structure and spatial distribution of slope inclination in morphological units, a significant difference between morphological units is evident. The category of 0–2° is generally scarcely present. In somewhat greater portions it is present on slopes of morphological units of Grabovica, Mesihovina, Ljubuša and Tomislavgrad hills. Inclination category of 2–5° is the most prominent in those same areas. Reasons for that are similar as in the previous category, but the intensity of various types of morphological processes is stronger. Inclination category of 5–12° is dominant in areas of morphological units of Ljubuša, Tomislavgrad hills, Grabovica, Mesihovina and Jelovača. This category features the duality of geomorphological processes of denudation and accumulation as well, depending on the lithological content. Categories of 12–32° are the most prominent in areas of morphological units of Tušnica, Vran, Lib, Jelovača and Mesihovina. It is present in other morphological units to a much lesser extent, being significantly scarcer than the category of 5–12°. Slope inclinations of category of 32–55° are present in an extremely low portion of the reasearched area, being prominent only in units of Tušnica and Lib. The main reason for that are morphological and morphostructural features of these two units, i.e. a greater portion of areas at high altitudes, exceptional terrain dynamics and frequent tectonic dislocations (faults, overthrusts and crusts). Inclinations greater than 55° are present in an extremely low portion, and only in the morphological unit of Lib, near the tectonically conditioned steep hillslopes at the middle ledge.

- Spatial distribution of slopes with various types of profile curvature shows significant parallelism with the directions of tectonic lines. These slopes are often grouped in larger areals with feature block structure or are stretched along a tectonic line. This primarily refers to parallelism of types of curvature, i.e. the alternation of convex and concave parts of slopes within blocks (Tušnica, Lib, Tomislavgrad hills) or elongated areals (Ljubuša, Grabovica, Jelovača, Lib). Correlation with the geological map shows that dislocations (faults, overthrusts, crusts) are present along the bordering elongated areas, at the contact of convex and concave areals. This is further confirmed by the distribution of slope inclination. Namely, in all of these instances, there is a greater portion of relatively steeper inclination categories (especially those of 12–32°), which additionally indicates the activity of neotectonic processes within the researched area.
- Unlike profile curvature, where elongated and block structure dominates the areal, those areas with various types of planar curvature feature dominant areals that are smaller in size (degradation) and which correspond with the distribution of concave and convex terrain forms (ravines and ledges, or karst depressions and mid-spaces). Greater degree of size degradation is notable within morphological units which have limestone as their basis, and which feature spacious flats covered by karst sinkholes and basins (Grabovica, Ljubuša, parts of Lib).
- A more detailed analysis of relations between individual inclination categories and types of profile curvatures, as indicators of the intensity and characteristics of neotectonic processes, has shown that these processes are the most prominent in the morphological units of Vran, Tušnica, Lib, Jelovača and Mesihovina (the greatest portions of convex and concave slopes and inclination categories of 12–32°, parallelism with tectonic lines), and not so prominent other morphological units (Ljubuša, Tomislavgrad hills and Grabovica) which feature dominant inclination of 5–12° and less parallelism with tectonic lines. Linear slopes are present in a much smaller portion, with the inclination category of 0–2° being dominant, mostly within the morphological unit of Grabovica and Mesihovina. In the unit of Tomislavgrad hills the situation is somewhat more complex, i.e. there is a balanced portion of slopes with inclination of 0–2° and 2–5°. That is a result of a specific lithological content (marl being dominant) which enabled a significant process of sedimentation in lower parts of hills, and which affected the shape of smoother slopes with inclination category of 2–5°.
- The analysis of relation between inclination category and types of planar curvature shows similarities, but also differences. Similarities are most evident in the fact that most morphological units are very much the same (having occasionally different distribution), considering the hierarchy of domination of morphometric indicators. Differences are mostly evident in spatial distribution and structure of slopes with planar curvature. On both convex and concave

slopes the dominant category is that of 12–32° in morphological units of Tušnica, Vran, Lib and Jelovača, which indicates a greater degree of intensity and complementarity of destructive processes of denudation on one side and accumulation on the other side, compared to other morphological units. Comparison with spatial distribution of slopes with profile convex and concave curvature indicates a similar hierarchical order of slope inclinations in categories of 12–32°, which indicates a combined effect of endogenous and exogenous processes. Exogenous geomorphological processes are of relatively lower intensity in morphological units of Ljubuša and Grabovica, which is a result of mainly limestone-based structure (domination of karstic corrosion). There is a specific situation within the morphological unit of Tomislavgrad hills. Namely, due to prominence of softer rock types in its base (Miocene marl), the intensity of denudation and accumulation causes a decrease in the level of inclination of those areas which are subject to denudation, and an increase in inclination level in those areas with intensive sedimentation, which is also indicated by data on slope structure (although the category of 12–32° is dominant, a relatively high portion of category of 5–12° is present nevertheless).

- Considering the relation between profile and planar curvature, field research confirms the result of digital model less suggestively (Parsons 1988), i.e. there is no signifying relation between profile and planar curvature, especially on those places which feature sheet washing more than soil creeping. Some connection can exist only in local instances. An important notion for prediction of slope-related processes based on planar curvature, according to some authors, is most notable in cases of sheet washing (Armstrong 1987, Parsons 1988). Some other researchers have also shown a positive but weak correlation between planar and profile curvature (Evans and Cox 1999).

Data obtained from the analysis of types of profile and planar curvature confirm the results from previous researches, i.e. a weak correlation between planar and profile curvature. This is important because the analysis was conducted on a relatively broad area, which enables generalization of previous results that were of local importance, i.e. obtained by analyzing narrow areas.

A great number of researches confirmed that the relation of slope inclination and curvature, together with lithological content, affect the slope-related processes (Carson and Kirkby 1972, Young 1971, Parsons 1988, Khanchoul and Altschul 2008), and, consequentially, the shape of a slope. This relation is implicitly introduced in some models of slope profile development (Kirkby 1985).

6. Conclusion

Quantitative-geomorphological research of slope inclination and curvature are of great practical importance, since the shape of a slope has a significant effect on the distribution of surface and underground water, and, by extension, the movement of various masses (Sidle et. al. 1985). E.g. on a concave slope or part of such slope there will be a concentration of underground water (basins and ravines), which results in water saturation of local ground, and hence an increased probability of landslide. On a concave slope or a part of it, a layer of ground (i.e. a cover which consists of non-consolidated or poorly consolidated material, residual or transported from someplace else) can be twice the thick than on a convex one, which makes the slope more susceptible to processes of movement of mass. Slope inclination, shape and location of hillslope play a significant role in determining the growth and development of vegetation, especially forests. At higher levels of hillslopes and their steeper parts, the loss of nutrients from the ground can be significant and water flows more intense, which results in a thinner layer of soil. Convex slopes are dryer, soil nutrients are scarce and the volume of soil is decreased. Concave slopes are more humid and feature soils richer in nutrients and less pronounced derrasion, which contributes to better conditions for the growth and development of forest vegetation.

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Značajke nagiba i ravninske zakrivljenosti šireg područja Duvanjskog polja

SAŽETAK. U ovom su radu analizirane, kvantitativne geomorfološke značajke (nagibi padina, profil i ravninska zakrivljenost) planinskoga rubnog područja Duvanjskog polja. Na oblikovanje ovoga područja utjecalo je niz prirodnih i društvenih utjecaja tijekom geneze i evolucije reljefa. Cilj je ovog istraživanja analiza kvantitativnih obilježja nagiba padina i zakrivljenosti morfoloških obilježja šireg područja Duvanjskog polja, tumačenje rezultata i sinteze. Moguć je detaljniji uvid u značajke nagiba i odvijenih procesa, a moguće je postići i vrednovanje prirodno dominantnih geomorfoloških procesa. Tijekom istraživanja posebna je pažnja posvećena detaljnoj geomorfometrijskoj analizi u GIS okruženju, na temelju digitalnog modela reljefa. Analiza je provedena u nekoliko faza: 1. komparativna analiza karakteristika nagiba temeljena na morfološkim obilježjima, 2. komparativna analiza zakrivljenosti nagiba i 3. analiza odnosa između nagiba i značajki zakrivljenosti. Sinteza uključuje interpretaciju dobivenih rezultata u širem kontekstu odnosa između morfometrijskih značajki i strukturno/litoloških značajki morfoloških jedinica.

Ključne riječi: *šire područje Duvanjskog polja, morfološke jedinice, nagib, profil i ravninska zakrivljenost, morfometrija, GIS, DTM.*

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