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GEOMORPHOLOGICAL STRUCTURE OF THE KREMENETS MOUNTAINS: MORPHOLOGICAL FEATURES, RELIEF TYPES AND PROBLEMS OF REGIONALISATION

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Abstract:
The Kremenets Mountains are among the characteristic areas of the Podolian Upland (Ukraine), which remains insufficiently studied. The study area was characterised using the main methods of automatic classification of landforms, namely the geomorphon method and the topographic position index (TPI). The obtained results were correlated with the geological maps of a bedrock and superficial Quaternary sediments, scale 1:200,000, to identify relief types within the Kremenets Mountains. The main types of relief of the Kremenets Mountains were categorised, and their regionalisation was carried out according to the reference landforms. Structural and denudational, denudational and fluvial types of relief were identified. Gravitational, karst, biogenic and technogenic landforms were also specified, including a field research. Morphometric maps of the study territory were constructed, and its main indicators were characterised according to equal-sized (1×1 km) squares, namely slope gradient, vertical and horizontal relief dissection. Analysis of these maps allowed us to identify regions with high, mean and minimum values of indices, which formed the foundations for separation of the geomorphological subregions within the Kremenets Mountains, namely Kremenets steeply sloping highly dissected subdistrict, Zalistsi moderately sloping meanly dissected subdistrict, and Kutianka gently sloping slightly dissected subdistrict.

Key words: geomorphons, topographic position index, relief types, morphometry, geomorphological regionalisation.

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INTRODUCTION

The Kremenets Mountains are an upland located in the northern part of the Podolian Upland, which is a subregion of the Volhyn-Podolian Upland geomorphological region, a component of the East European Plain within the territory of Ukraine. The Kremenets Mountains border the Voroniaky Upland to the west, the Khmelnytskyi Plateau to the south and east, and the Male Polissia lowland to the north.

Administratively, it is part of the Kremenets district of the Ternopil region. The average absolute altitude marks here are 370–400 m a.s.l., and the maximum is the Drabanykha Hill (408 m a.s.l.). The upland has clear orographic boundaries: the northern boundary is formed by the North Podolian escarpment, the western by the valley of the Ikva River, the eastern by the Vilia River, and the southern by the headwaters of their tributaries.

It should be noted that from a geomorphological point of

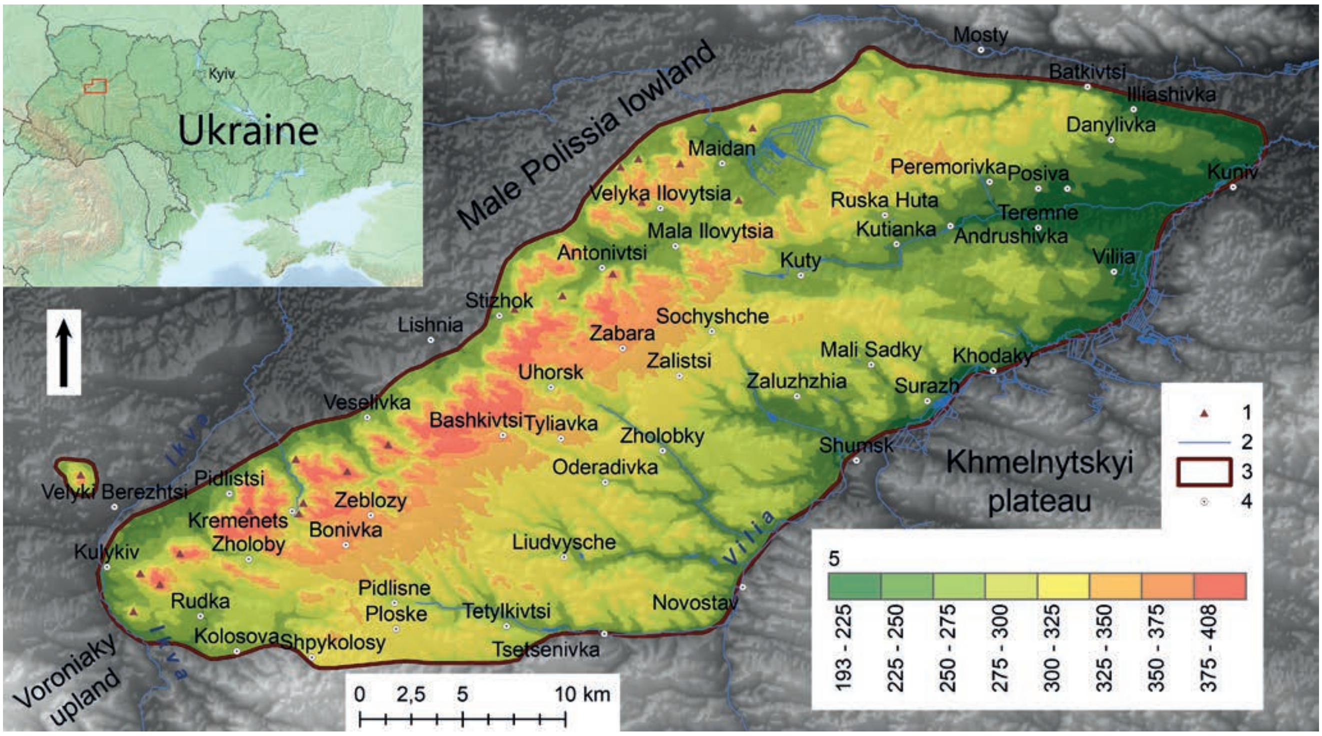

Fig. 1. Digital elevation model of the Kremenets Mountains: 1 – main peaks, 2 – water bodies, 3 – upland limits, 4 – settlements, 5 – elevation (m a.s.l.).

view, the Kremenets Mountains are not typical mountains, and such a name is incorrect. This is a toponym formed historically due to significant (more than 100 m) relative elevations of the upland above the bottom of the Male Polissia lowland (Fig. 1). The names of the Kremenets Upland or Kremenets Hills would be more appropriate.

Many scientists were engaged in geological and geomorphological studies of the upland territory in the 19th–21st centuries. The first works on the research of the Kremenets Mountains were related to the hypotheses of the formation of the northern escarpment of Podillia (Teyisseire, 1893; Łomnicki, 1895; Zierhoffer, 1927; Smoleński, 1910; Pawłowski, 1910; Jahn, 1989). One of the first fundamental works describing the geological structure and relief of the Kremenets Mountains is the monograph of Laskarev (1914). The next one should mention the research of geological survey expeditions and their compilation (by collecting actual material and borehole drilling data) of geological and tectonic maps. In the 20th century, the study of the Kremenets Mountains was a part of the study of the Podolian Upland and the singling out of its constituent part – the Holohory-Kremenets Ridge (Tsys, 1962; Herenchuk, 1979; Palienko, 2013). Also, at this time, the territory of the upland is studied in the context of thematic geological and geomorphological research, such as planation surfaces (Marynych and Palienko, 1998; Bogucki and Svynko, 1975), modern tectonic movements (Svynko, 1968, 2007; Palienko, 2013), the flow direction of the river network and the fracturing of Neogene and Cretaceous sedimentary rocks (Svynko, 1965, 1975). Current geomorphological research is related to the local history study of the territory and its ecological and educational value in connection with the creation within its borders in 2009 of the Kremenets Mountains National Park (Shtogryn *et al.*, 2017).

The issues of identifying types and forms of relief, creating a geomorphological map, and carrying out geomorphological regionalisation are essential and need to be resolved. There are numerous of our publications on morphometric, morphotectonic, and structural and geomorphological topics (Bermes, 2015, 2016, 2018, 2019, Bermes *et al.*, 2018, 2024; Bermes and Tomeniuk, 2020) that characterise the importance of the study of the Kremenets Mountains. This publication attempts to fill the gap in the study of a particular geomorphological region of Ukraine and present the results of geomorphological mapping and regionalisation of the research area.

MATERIAL AND METHODS

The research is based on the field research results within the Kremenets Mountains and desk work on creating a digital elevation model. The ASTER Global Digital Elevation Map (tiles for zones N50E025 and N50E026) served as the cartographic basis for the study. Automatic classifications of its morphological components, namely geomorphons and topographic position index (TPI), were performed to determine the boundaries between terrain types (Jasiewicz and Stepinski, 2013; Guisan *et al.*, 1999). SAGA 9.3.0 (Conrad *et al.*, 2015) software was used for this purpose. Automatic classification of geomorphons was carried out using the following actions: Geoprocessing – Terrain Analysis – Terrain

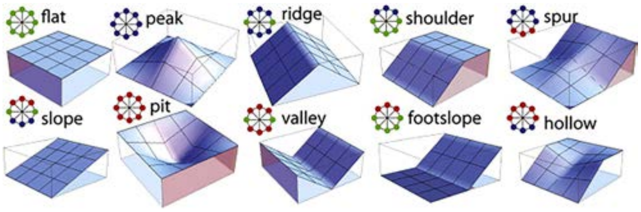

Fig. 2. The most frequent and commonly recognisable geomorphons (Jasiewicz and Stepinski, 2013).

3	4	3	2
3	3	5	3
2	3	4	3
1	3	3	2

a

C	A	B	B
C	D	A	B
D	C	A	C
D	C	C	C

b

Fig. 3. The scheme of conditional hypsometric levels (*a*) and geomorphons (*b*) for the area of the residual hill of Bozha: *a.* 1–5 – hypsometric levels, where 1 – the lowest elevations, 5 – the highest elevations; *b.* A – class “Ridge”, B – class “Hollow”, C – class “Slope”, D – class “Valley”.

Classification – Geomorphons. For the TPI, the actions looked like this: Geoprocessing – Terrain Analysis – Terrain Classification – TPI Terrain Based Classification.

Geomorphons are a categorization of terrain types determined by the search radius for similarity of pattern conditions and uniformity of cell sizes. In general, elevation levels from a target cell in all directions are identified, and eight neighbouring cells are analysed. This procedure is repeated for all cells within the study area with the definition of the geomorphon class (Fig. 2).

An increased search radius is used for a more detailed display and assessment of the relief situation in a larger territory, which, in turn, raises the number of neighbouring cells that are analysed. For example, this is how the scheme of conditional hypsometric levels and geomorphons for the area of the residual hill of Bozha looks like (Fig. 3).

There are some publications about the method of construction and classes of geomorphons. In particular, J. Jasiewicz and T.F. Stepinski were the first to apply this method to classify landforms (Jasiewicz and Stepinski, 2013; Jasiewicz *et al.*, 2013; Woźniak, 2015). Further publications were based on using this methodology for various research areas. For instance, Rowley *et al.* (2018) characterised the peculiarities of creating geomorphon maps in the territory of North Carolina state (USA). Kramm *et al.* (2017) gave the geomorphological characteristics using geomorphons of the territory of the Iranian Loess Plateau with a comparison of different digital elevation models (SRTM, ASTER). Silveira *et al.* (2018) created the geomorphon maps and compared them with geomorphological maps of the Paraná state region (Brazil). They analysed the generated classes of geomorphons by geomorphological areas. Gawrysiak and Kociuba (2020) analysed the morphological changes of the relief of the proglacial valley by using the geomorphons method.

The TPI reflects the change in the level of the topographic surface relative to its average elevation level. For the studied cell with constant dimensions, the search radius of the mean elevation level is predetermined, which results in obtaining positive, negative or zero index values, which identify the landscape’s upper, lower and middle parts.

It should be noted that when the search radius is changed, the value (class) of the result may vary significantly (Fig. 4) (Jenness, 2006). This technique was first used by Wilson and Gallant (2000), and a modification for the class selection method was developed by Weiss (2001) (Table 1). TPI is often used in regional geomorphological studies (Gerçek and Zeydanli, 2010; Barka *et al.*, 2011; De Reu *et al.*, 2013; Mokarram *et al.*, 2014; Rowley *et al.*, 2018; Trentin *et al.*, 2016). The definition of TPI can be considered in the example of the residual hill of Bozha with a search radius of 3 cells (Fig. 5).

Table 1. Ten-class landform categories by A.D. Weiss (2001). TPI: topographic position index.

Landform categories	Slope	Small neighbourhood	Large neighbourhood
Canyons	–	TPI ≤ – 1	TPI ≤ – 1
Shallow valleys	–	TPI ≤ – 1	– 1 < TPI < 1
Upland drainages	–	TPI ≤ – 1	TPI ≥ 1
U-shape valleys	–	– 1 < TPI < 1	TPI ≤ – 1
Plaines	≤ 5°	– 1 < TPI < 1	– 1 < TPI < 1
Open slopes	–	– 1 < TPI < 1	– 1 < TPI < 1
Upper slopes	> 5°	– 1 < TPI < 1	TPI ≥ 1
Hills in valleys	–	TPI ≤ 1	TPI ≤ – 1
Midslope ridges	–	TPI ≤ 1	– 1 < TPI < 1
High ridges	–	TPI ≤ 1	TPI ≥ 1

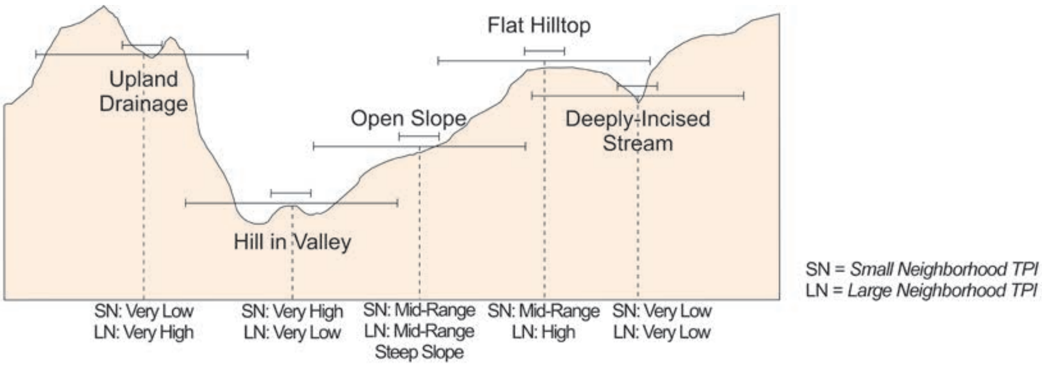

Fig. 4. Landform classification using different scales of topographic position index (Jenness, 2006).

3	4	3	2
3	3	5	3
2	3	4	3
1	3	3	2

a

0	+	+	-
0	0	++	0
-	0	+	0
- -	0	0	-

b

Fig. 5. The scheme of conditional hypsometric levels (*a*) and topographic position indexes (*b*) for the area of the residual hill of Bozha: *a.* 1–5 – hypsometric levels, where 1 – the lowest elevations, 5 – the highest elevations; *b.* ++ – significantly higher levels than the average (class “High ridges”), + – higher levels than the average (class “Open slope”), 0 – approximately equal values to the average (class “Plains”), - – lower levels than the average (class “Upland drainages”), -- – significantly lower levels than the average (class “Streams”).

The geomorphological regionalisation scheme proposed here was based on morphometric features of the relief of the upland, namely the steepness of its surface, depth and density of terrain dissection. In the ArcGIS 10.2 software (ESRI 2011), automatic classifications have been made through the modules Slope for slope gradient, Line density for dissection density, and Focal statistic (max; min) for the depth of surface dissection.

The authors’ many years of fieldwork experience in the Kremenets Mountains was useful in this study. In the field, relief elements and forms were identified and mapped, their morphometric and genetic features were characterised, modern geomorphological processes were studied, etc. The results of field research were taken into account during the construction of a geomorphological map and a map of geomorphological regionalisation.

The final cartographic constructions (geomorphological map, map of geomorphological regionalisation) in the study were carried out in the ArcGIS 10.2 software using the materials of own field studies, geological (bedrock) and quaternary sediment (superficial) maps of the Rivne Geological Survey Expedition in scale 1:200,000 (Zelinski, 2011; Sudovtsev *et al.*, 1984), as well as automatic interpolations of morphological and morphometric characteristics of the terrain. The maps were built based on the selection of types and forms of relief and the method of carrying out detailed geomorphological regionalisation, described in numerous publications (Kravchuk, 1991, 2006).

RESULTS AND DISCUSSION

The analysis of geomorphons and the topographic position index (TPI) is one of the defining methods used to study the morphological features of the relief (Pál and Albert, 2021; Savka and Shushniak, 2019).

Geomorphons are component elements of the relief form. Each raster cell is assigned information about its location relative to 8 cells in variable proximity, which is set by the operator through the search radius parameter L and relates the surface elevation to the horizontal distance using the so-called zenith and nadir angles (Syzenko, 2023).

Within the uplands, automatic sampling identified ten morphological types of clusters, namely: 1 – flat, 2 – summit, 3 – ridge, 4 – shoulder, 5 – spur, 6 – slope, 7 – hollow, 8 – footslope, 9 – valley, 10 – depression (Fig. 6).

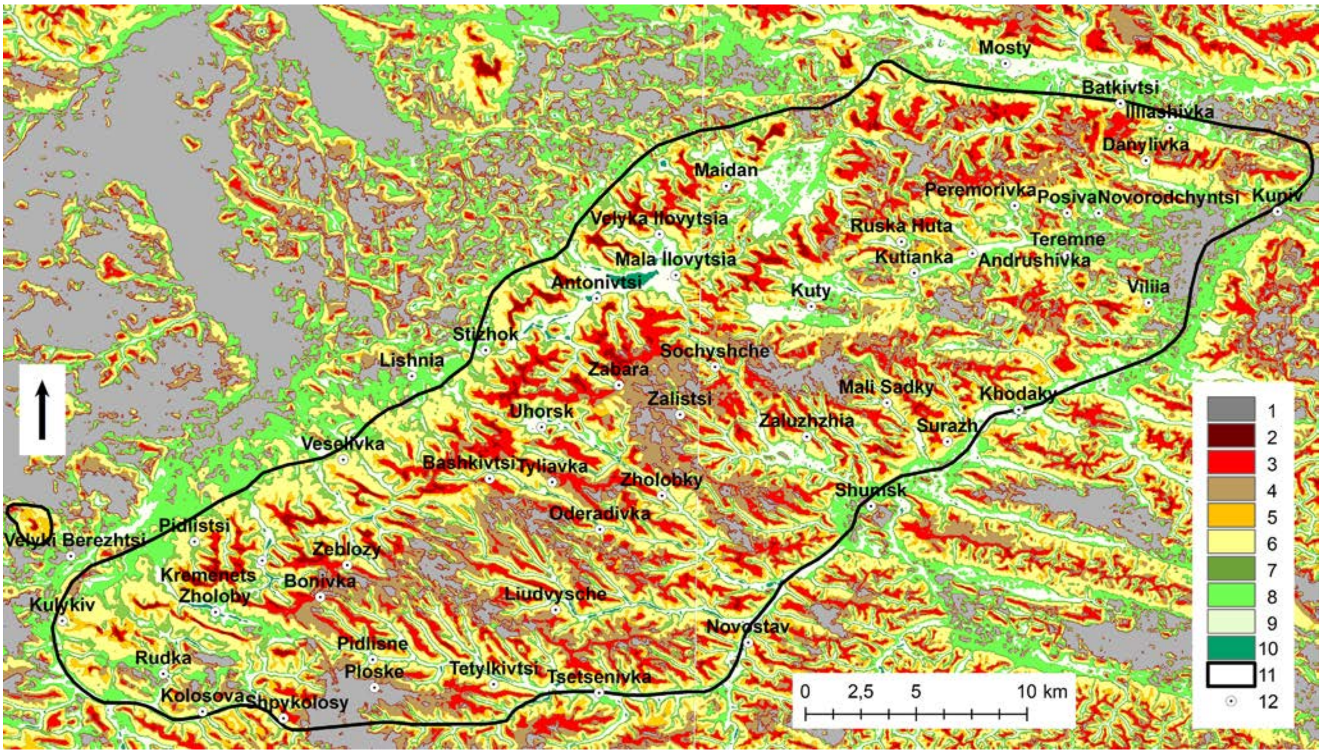

Fig. 6. Geomorphons. 1 – flat, 2 – summit, 3 – ridge, 4 – shoulder, 5 – spur, 6 – slope, 7 – hollow, 8 – footslope, 9 – valley, 10 – depression. *Other symbols:* 11 – upland limits, 12 – settlements.

The following classes of geomorphons have been defined for the territory of the Kremenets Mountains. Flat (1) is levelled territories with a slope gradient of less than 2°, confined to both plateau-like watershed surfaces and subhorizontal parts of valleys. Summit (2) is the highest area with a slope gradient of more than 2°, coinciding with the tops of the upland's residual hills and watershed surfaces. The opposite to the last ones is the identification of Depression (10), the territory within the valley surfaces, characterised by a lowering surface with a slope gradient of more than 2° in contrast to the neighbouring areas. There is a significant depression in the vicinity of the Antonivtsi and Mala Ilovytsia villages within the study area. Ridge (3) is the uppermost elongated part of the slope characterised by a convex curvature in plan and a slight degree of slope gradient of 2–5°. Territories located hypsometrically below the Ridge and characterised by higher values of surface steepness and concavity of forms are defined as Shoulder (4). Valley (9) characterises morphological forms associated with permanent and temporary watercourses of a concave shape in plan, namely morphological bottoms of valleys. Slopes as morphological components of landforms are presented in the categories of geomorphons: Spur (5) is the upper parts of the slopes of convex curvature; Slope (6) is the middle part of the slope with a dominantly straight shape, both in plan and profile, Hollow (7) – the lower part a predominantly concave slope, and Footslope (8) – stepped slopes prevailing in its lower part.

The analysis of morphotypes (geomorphons) showed clear boundaries of the main polygonal components of the relief, notably the summit, slope and bottom surfaces, as well as significant dissections of the main watershed and perpendicular ridge-like surfaces which branch out from it. The erosional network of thalwegs is clearly indicated, but the structure of permanent watercourses is rather weakly traced.

The TPI is a parameter used to analyze a topographic surface. It is defined as the plane deviation of a given point's elevation from the plane's mean elevation at a certain distance. It can have both positive and negative values, indicating whether the point is above, below, or at the same level as the average level of the area (Syzenko, 2023). Automatically generated classes are divided into ten categories: 1) canyons, deeply incised channels (streams); 2) midslope drainages, shallow valleys; 3) upland drainages, headwaters; 4) U-shaped valleys; 5) plains; 6) open slopes; 7) upper slopes, plateau; 8) local ridges, hills in valleys; 9) midslope ridges, small hills in the plains; 10) mountain tops, high ridges.

Using the TPI method, the following hypsometric levels were specified for the territory of the Kremenets Mountains: summit areas that differ in elevation and slope gradient (High ridges, Midslope ridges, Local ridges), morphological steep slopes (Upper slope, Open slope), morphological gentle slopes (Plains, Valleys), as well as bottom areas within permanent and temporary watercourses (Upland drainages, Midslope drainages, Streams).

The analysis of the obtained results clearly showed gullies and dry-valley networks, which have a wide distribution along the entire North Podolian escarpment and the valley of permanent and temporary watercourses. The elevation structure of the upland and its uppermost part of the watershed component is somewhat worse displayed (Fig. 7).

The analysis of geomorphons and the TPI made it possible to evaluate the morphological features of the landform,

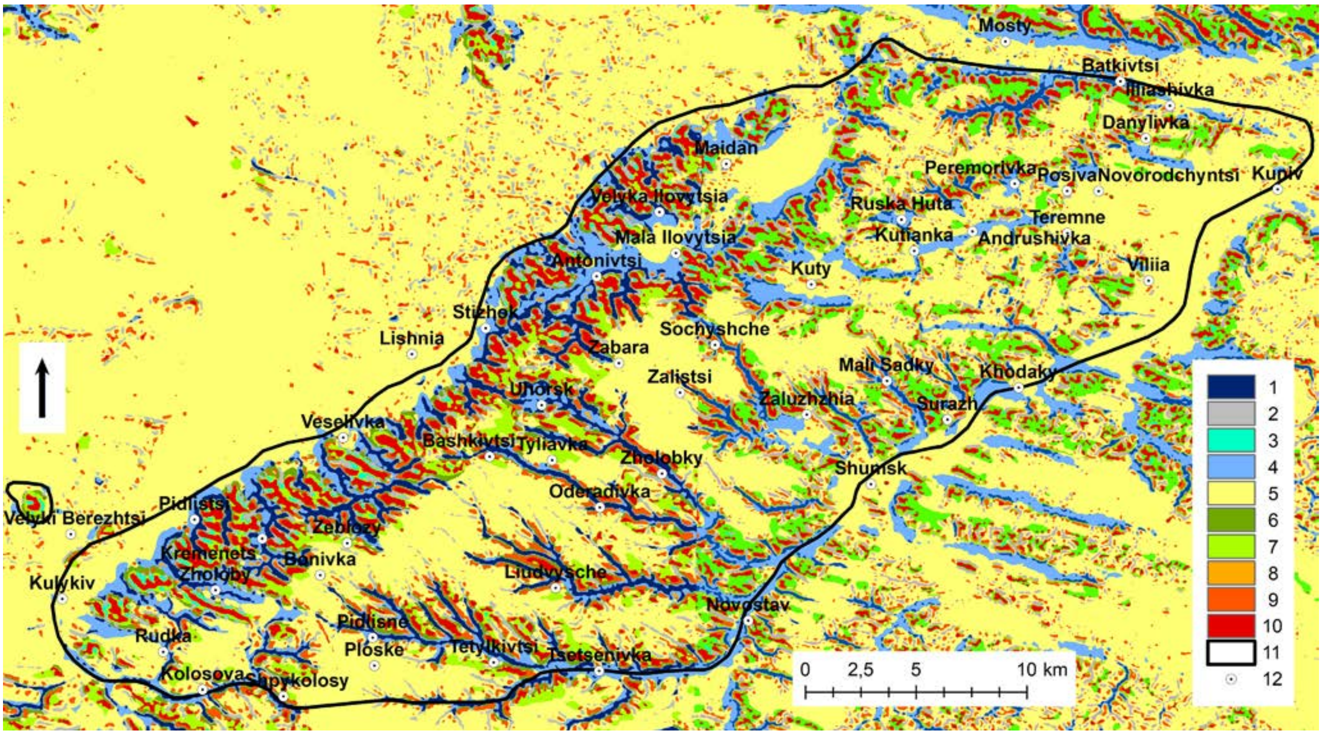

Fig. 7. Topographic Position Index (TPI). 1 – streams, 2 – midslope drainages, 3 – upland drainages, 4 – valleys, 5 – plains, 6 – open slope, 7 – upper slope, 8 – local ridges, 9 – midslope ridges, 10 – high ridges. *Other symbols:* 11 – upland limits, 12 – settlements.

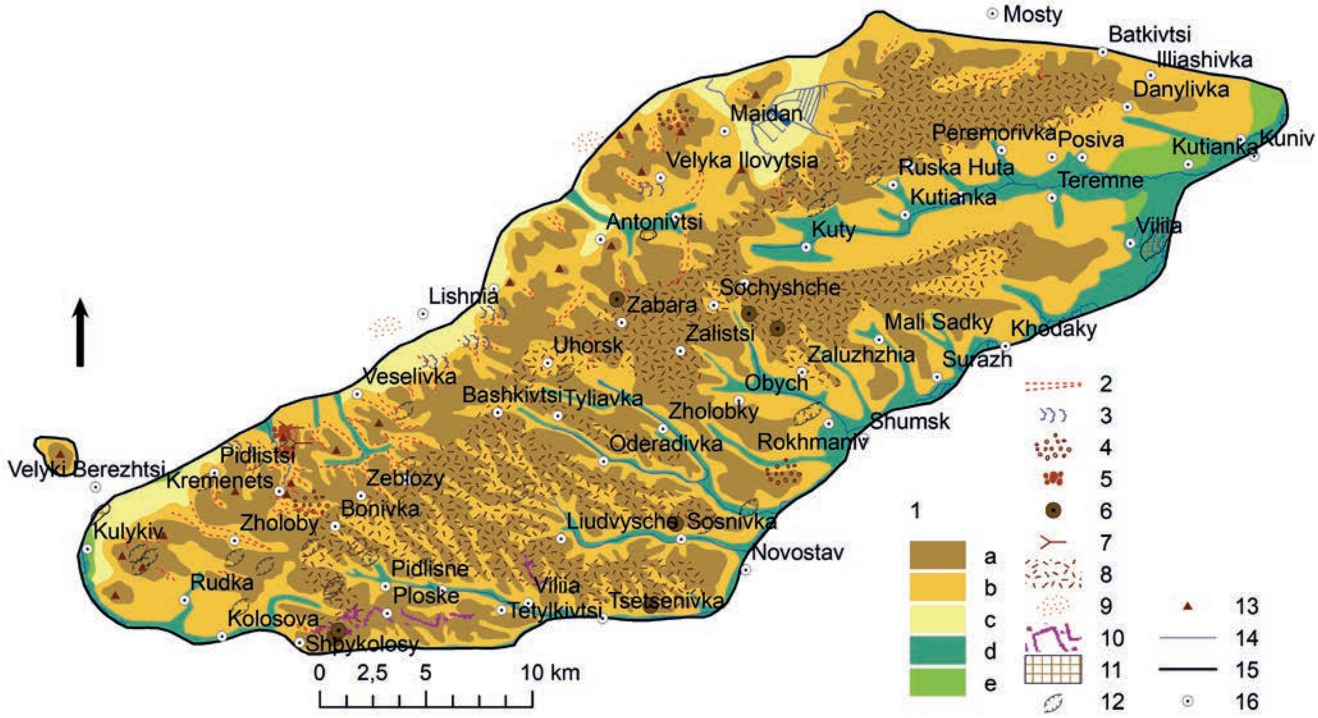

Fig. 8. Geomorphological map of the Kremenets Mountains. 1 – *Types of relief*: a – structural and denudational (on Neogene deposits); b-c – denudational (b – denudation slopes, c – the bottom of the denudation plain on Cretaceous deposits); d-e – fluvial (d – floodplain, e – the first terrace). *Landforms*: fluvial: 2 – gullies; 3 – alluvial fans; gravitational: 4 – landslide accumulations; 5 – forms of rock topples on the steep slopes; karst: 6 – sinkholes and saucer-like depressions, 7 – caves, 8 – areas of distribution of karst landforms; aeolian: 9 – dunes; paleocryogenic: 10 – polygonal forms; biogenic: 11 – peat bogs; technogenic: 12 – quarries. *Other symbols*: 13 – main peaks; 14 – water bodies; 15 – study area limits; 16 – settlements.

particularly its types and specific forms and elements of the relief. On medium-scale maps, it is advisable to use both of these methods. Combining the results obtained from the construction of geomorphons and the TPI maps makes it possible to discuss the boundaries of relief types in more detail. As for the limits of landforms, these maps show only their approximate outlines.

On the Ukrainian geomorphological and morphostructural maps, the Kremenets Mountains are distinguished as structural and denudation uplifts, namely horst and monoclinal uplands on the Neogene deposits. In the geomorphological structure, we distinguish the following genetic types of relief: structural and denudational, denudational, and fluvial (Fig. 8).

The structural and denudational type of relief is typical for the territory of the Kremenets Mountains in the form of residual hills that extend along the upland's escarpment and through its summit areas. A whole complex of geological formations characterises the relief. The geological structure of the territory includes the Cretaceous deposits of the Cenomanian and Turonian stages, represented by chalk and marl. The Neogene deposits lie above them, namely the Badenian sands, sandstones, and the Sarmatian limestones (Zelinski, 2011; Sudovtsev *et al.*, 1984). The structural and denudational relief is typical for the watershed territories covered with aeolian-deluvial loess-like loams and eluvial deposits. It is characterised by elevations of 360–408 m, which is the maximum for the topography of the upland.

The denudational relief is widespread within the Kremenets Mountains and the adjacent part of the Male Polissia lowland. It is built by the Cretaceous and by the Quaternary sandy deposits. Slopes characterised by deluvial washout and accumulation processes are widely distributed. Slightly hilly landforms of aeolian origin (dunes) are also evident on this plain.

The fluvial relief is represented by an extensive network of Ikva and Vilia River valleys and its tributaries. Within the studied territory in the valley of the Ikva River, a floodplain complex and one river terrace can be distinguished relatively clearly. A floodplain and the first terrace can be observed in the Vilia and Kutianka Rivers valleys. Also, the fluvial erosional relief is represented by a strongly branched system of gullies and dry valleys throughout the territory of the Kremenets Mountains. At the foothill of the escarpment, there are several accumulative landforms, such as alluvial fans (within the localities of Bilokrynytsia, Lishnia, etc.). The fluvial topography is formed mainly by alluvial and proluvial deposits of the Late Pleistocene and Holocene.

Gravitational, karst, and anthropogenic landforms do not have a wide spatial distribution on the territory of the Kremenets Mountains. Still, they are mainly represented by the correlative type of landforms scattered throughout the upland territory. Gravitational forms are represented by landslide accumulations and blocks formed due to mass wasting processes along the slopes, particularly rock topples, which are mainly concentrated on the steep slope of the Kremenets Mountains along the escarpment. Karst terrain is represented by surface and underground landforms. Among the surface ones, the most common are karst sinkholes and saucer-like karst depressions. These forms are distributed over almost the entire territory of the Kremenets Mountains and are characterised as negative landforms. Biogenic relief, namely peat bogs, is formed in the valley of the Ikva River, north of the town of Kremenets. Quarries represent technogenic or anthropogenic landforms. Some of them are vast enough (for instance, the chalk quarry in the village of Pidlistsi) and occupy large areas.

Some other forms of relief can also be distinguished in the relief of the Kremenets Mountains. In particular, the escarpment of the Kremenets Mountains is clearly reflected in the relief as a fragment of a regional fault and can be attributed to tectonically determined landforms. Denudation landforms include pediplains as fragments of planation surfaces near the Maidan village and pediment slopes of the Kremenets Mountains. As denudation forms of relief, it is worth considering residual hills, in the formation of which erosion processes also played an active role. In the southern part of the Kremenets Mountains, a large polygonal network of paleocryogenic origin is developed on the territories covered by loess.

The Ikva floodplain at the Podolian section of the valley has a width of up to 100 m, in some places, it is slightly larger. After the river reaches the Male Polissia lowland, its width increases to 1–2 km. It rises above the river level by an average of 0.5–1.0 m. The surface of the floodplain is flat, often swampy. It is composed of sandy loam deposits, occasionally with fragments of chalk and marl 2–3 cm in diameter, and peat (Svynko, 1975). The first terrace can be traced intermittently along almost the entire river length. Its height above the water level is, on average, 6–8 m.

Microforms of rill and sheet erosion are common along riverbeds and on steeply sloping surfaces.

Approaches to geomorphological regionalisation

The essence of geomorphological regionalisation is the division of the Earth's surface into geomorphological territorial taxa of different ranks with geomorphological features that distinguish it from others (Stetsyuk and Kovalchuk, 2005). Many scientists conducting geomorphological research attempted to regionalise the territory of the Kremenets Mountains. Laskarev (1914) was one of the first to distinguish the Kremenets Mountains into an individual taxonomic geomorphological unit.

After the Second World War, the geomorphological regionalisation of the territory of Ukraine was developed by Bondarchuk (1949). From a taxonomic point of view, the territory of the Kremenets Mountains was separated into a particular geomorphological division: the geomorphological country Polygenic Plain → the region of the Volhynian-Podolian Plateau → the Kremenets Table Mountains. However, Bondarchuk (1949), under the Kremenets Table Plateau, considered the territory lying on the watershed between the Seret, Zbruch, Bug, Horyn, and Ikva Rivers. That is, in the modern geomorphological regionalisation, this is the territory of the Kremenets Mountains, Voroniaky Upland and the northern part of the Middle Podolian Upland (Khmelnytskyi and Ternopil structural and denudation upland) (Herenchuk, 1979).

Classic for the territory of Ukraine is the regionalisation system developed in the middle of the 20th century (Tsys, 1962), which is based on the genetic features of the land surface, particularly the types of relief. Within the territory of the study area, he distinguished such hierarchy of geomorphological units: the Polygenic plain of the Ukrainian SSR → the region of the Volhynian-Podolian Upland → the subregion of the Podolian Upland → the district of the Holohory-Kremenets low-mountainous edge of Podillia with adjacent residual hill groups. The Hologory-Kremenets low-mountain edge of Podillia is divided from west to east into three parts: the Hologory, the Voroniaky, and the Kremenets Mountains. Thus, the Kremenets Mountains are determined as an individual geomorphological unit from the Ikva River to the Zbytenka River.

Geomorphological regionalisation, developed by Palienko *et al.* (2004), is based on features of the relief caused by morphostructural, morphosculptural, morphological and morphometric differences. According to it, the Kremenets Mountains are part of the Hologory-Kremenets range, taxonomically distinguished within the following geomorphological hierarchy: East European plain geomorphological country → Volhynian-Podolian region of structural denudational uplands → subregion of the Podolian structural denudation upland on Neogene and Cretaceous deposits → Hologory-Kremenets structural denudation highly dissected Hill Ridge (Palienko *et al.*, 2004). Therefore, in this case, identifying the Kremenets Mountains as a taxonomic unit of geomorphological regionalisation is possible at the subdistrict level. The geomorphological neighbours of the Kremenets Mountains as part of the Hologory-Kremenets Hill Ridge are the subregion of the Male Polissia structural accumulative plain, namely the districts of the Brody and Slavuta alluvial and glacio-fluvial plains in the north and east, respectively. To the west of the Kremenets Mountains is the Voroniaky upland, which is distinguished by the authors as the hill ridge. In the south, behind the valley of the Vilia River, the district of the Khmelnytskyi structural denudation moderately dissected upland stretches, which also belongs to the Podolian geomorphological subregion. The North Podolian escarpment is the boundary between the Male Polissia and Podillia subregions in the characterised zoning.

According to Tsys (1962), a geomorphological district is a territorially separated unit characterised by a specific, unique combination of several types of relief or one type. Within its boundaries, geomorphological subdistricts are distinguished, the markers of which are distinctive features of morphometry and morphology of the relief.

In geomorphological regionalisation, this article uses the approach of distinguishing geomorphological subdistricts based on the morphometric features of the Hologory-Kremenets structural denudational highly dissected hill range. Within the territory of the Kremenets Mountains, the morphometric indexes taken into account are slope gradient, horizontal (density) and vertical (depth) dissection. The residual hill of Bozha (Buzha) is assigned to the territory of the Kremenets Upland based on sameness in the geomorphological structure and geological structure of the deposits that form it.

Morphometric maps

To characterise the steepness of the terrain surface, a thematic map of the territory of the Kremenets Mountains was built (Fig. 9). It clearly reflects the northern edge of Podillia. The average value of the slope gradient within the studied territory is about 3.2°. Its highest values (>20°) are associated directly with the north escarpment, residual hills and the territory of the gullies and dry-valley networks near the settlements of Kremenets, Pidlistsi. The maximum steepness of the slopes (23.3°) is documented in a gully near Kremenets. The minimum values are typical for plateau-shaped watersheds. Here, the slope gradient approaches 0° and occasionally exceeds 2°. Over 50% of the study area is occupied by slopes with a steepness of up to 6°, while slopes with a gradient of more than 20° occupy only up to 5% of the territory. Average values of the index generally have an uneven distribution: in the north-western part of the Kremenets Mountains, it is approximately 9.8°, and in the southeastern part is about 1.5°. Whereas the value of the indicator was determined for an area of 1 km^2, it can be concluded that high values of slope gradient characterise the upland because similar maximum values among neighbouring territories are characteristic of the escarpment within the Hologory Upland (Bogucki and Svynko, 1975), as well as the southern escarpment of the Mizoch Upland (Novak, 2013).

The density of horizontal dissection of the terrain of the Kremenets Mountains reflects the branching of the river and gully network (Fig. 10). The maximum values of this index are typical for the northwestern, southern, and southeastern parts of the study area. The maximum value, 2.3 km/km^2, is near the settlements of Bilokrynytsia and Shumsk. The minimum values are typical for elevated regions of the territory (>350 m) and only sometimes exceed 0.5 km/km^2. The mean value of the density of relief dissection on the upland territory is 0.7 km/km^2.

The analysis of the map, which showed the depth of vertical dissection of the terrain (Fig. 11), demonstrated results similar to the slope gradient indicator. The highest values of the elevation difference are typical for the territory of the northern escarpment, the plateau-like part of the Kremenets Mountains, and the residual hills north of the escarpment (48–90 m/km^2).

The mean values of the vertical dissection indicators of the Kremenets Mountains terrain vary in the range of 13–14 m/km^2. The lowest values (up to 5 m/km^2) are typical for the plain areas of the depression of the territory and the eastern part of the study area. These values can be explained by the fact that the distribution of elevations per unit area is high precisely in the territory with a strongly branched system of gullies and dry valleys, and the interfluve areas between them occupy a relatively small area. This is a reason for the high values of this morphometric indicator in the upland. The lowest values recorded in the eastern part of the Kremenets Mountains are due to low absolute heights and a low value of the distribution of heights as these are the areas of the confluence of the Vilia and Kutianka Rivers.

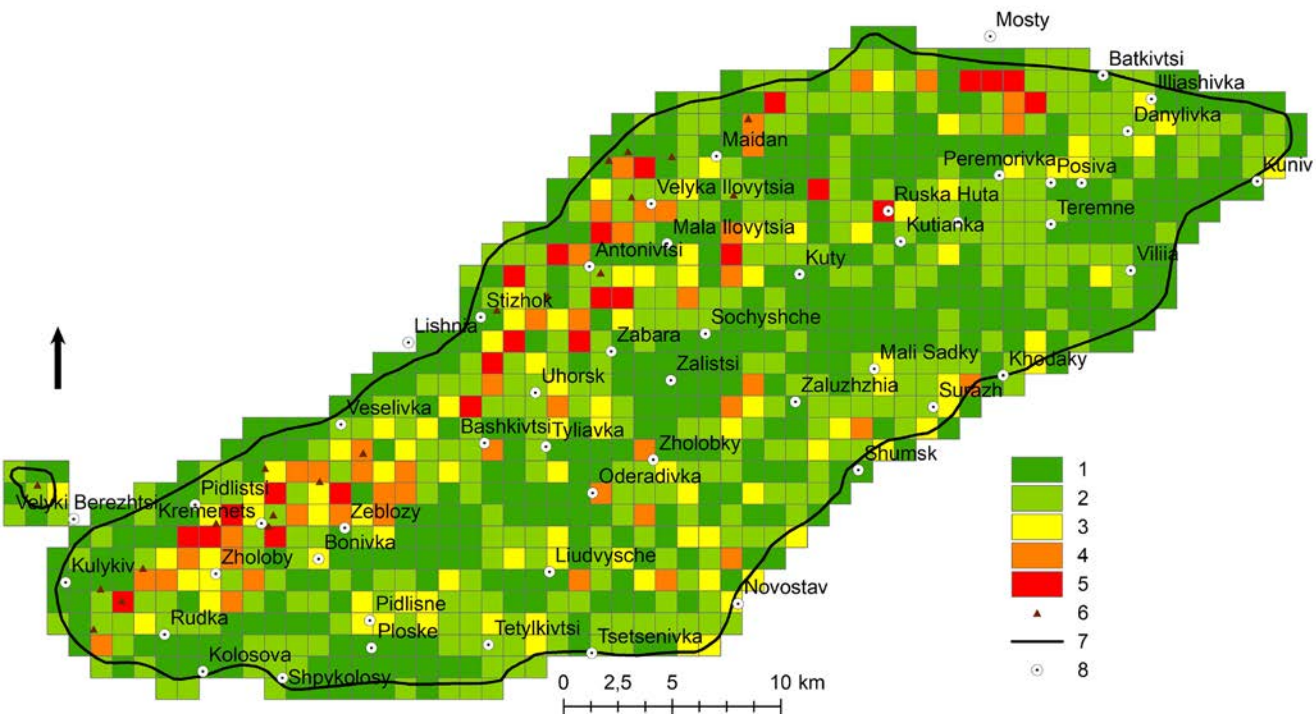

Fig. 9. Slope steepness map. *Slope gradient*, degrees: 1 – 0–2.0, 2 – 2.1–4.0, 3 – 4.1–7.0, 4 – 7.1–12.0, 5 – >12.1. *Other symbols*: 6 – main peaks, 7 – study area limits, 8 – settlements.

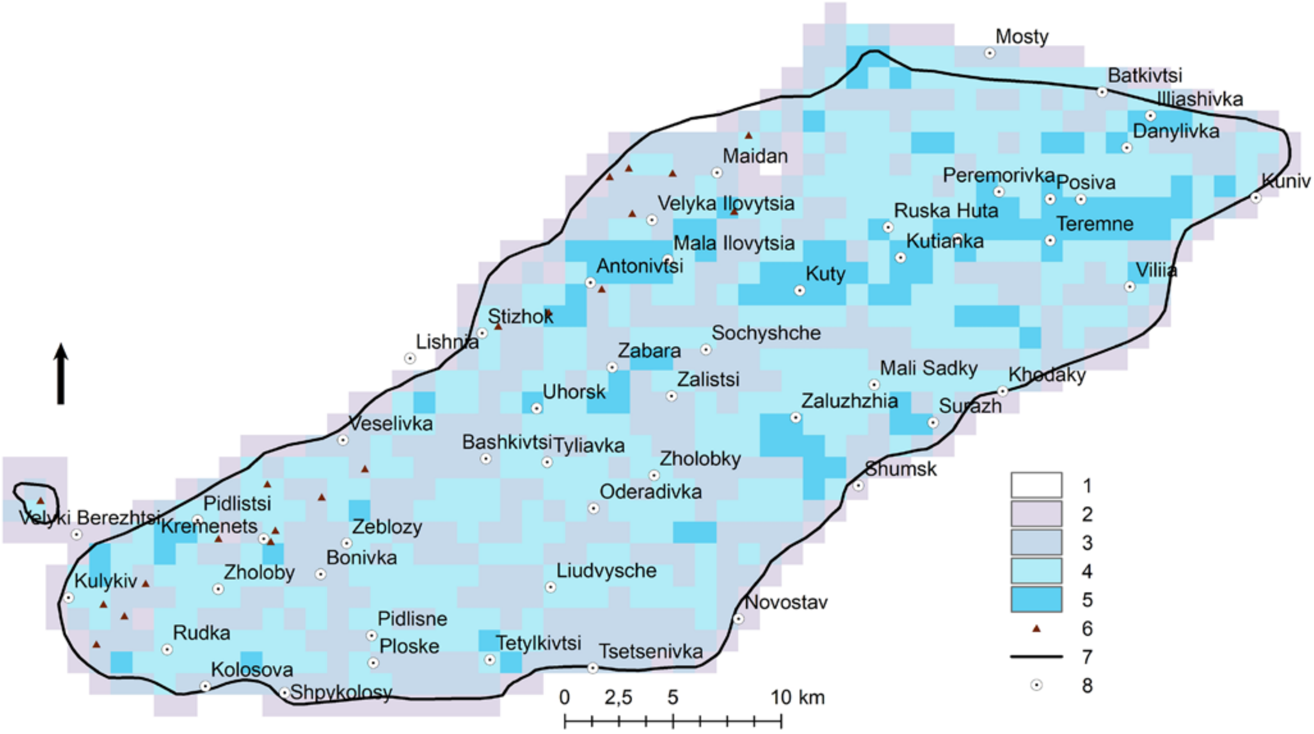

Fig. 10. Map of the dissection density of the terrain. *Dissection density*, km/km^2: 1 – 0–0.5, 2 – 0.6–1.0, 3 – 1.1–1.5, 4 – 1.6–2.0, 5 – >2.1. *Other symbols*: 6 – main peaks, 7 – study area limits, 8 – settlements.

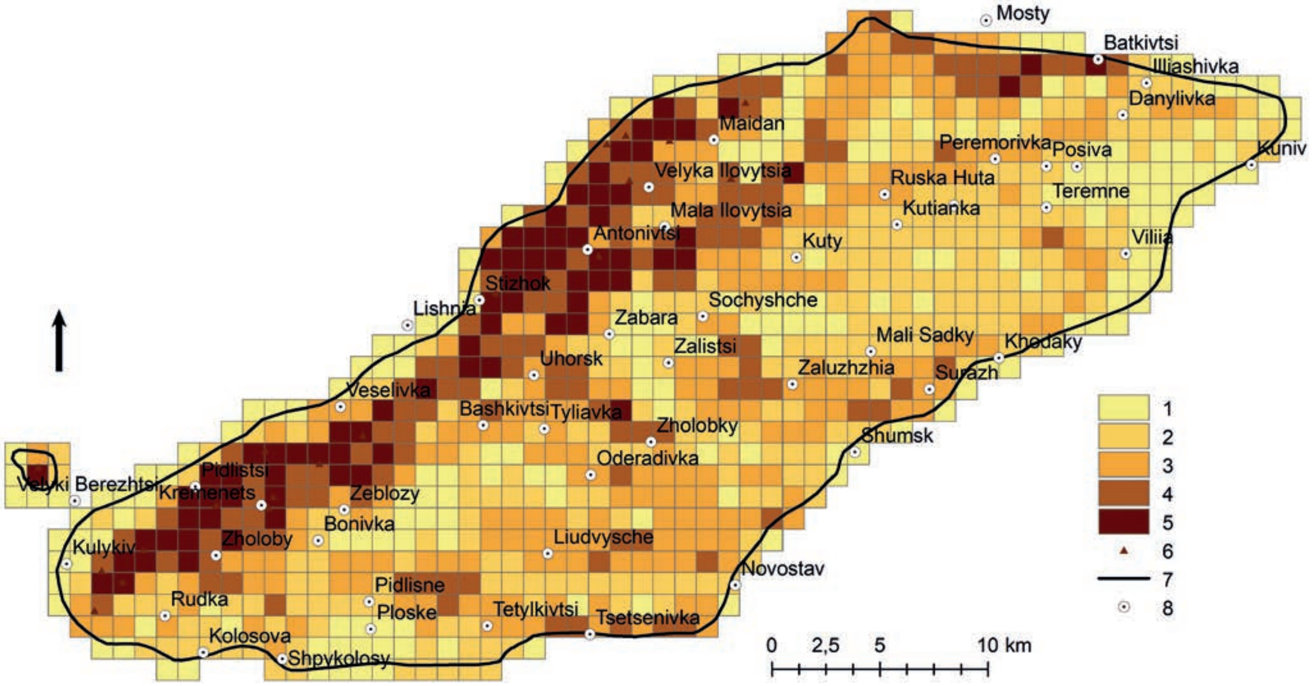

Fig. 11. Map of vertical dissection of the terrain. *Depth of dissection*, m/km^2: 1 – 0–10.0, 2 – 10.1–20.0, 3 – 20.1–30.0, 4 – 30.1–40.0, 5 – >40.1. *Other symbols*: 6 – main peaks, 7 – study area limits, 8 – settlements.

Proposed geomorphological regionalisation of the Kremenets Mountains

Three geomorphological subdistricts were identified within the Kremenets Mountains due to complex morphometric analysis (Fig. 12):

1) Kremenets steeply sloping highly dissected subdistrict;
2) Zalistsi moderately sloping meanly dissected subdistrict;
3) Kutianka gently sloping slightly dissected subdistrict.

The boundaries of the defined subdistricts are determined based on a complex analytical morphometric indica-

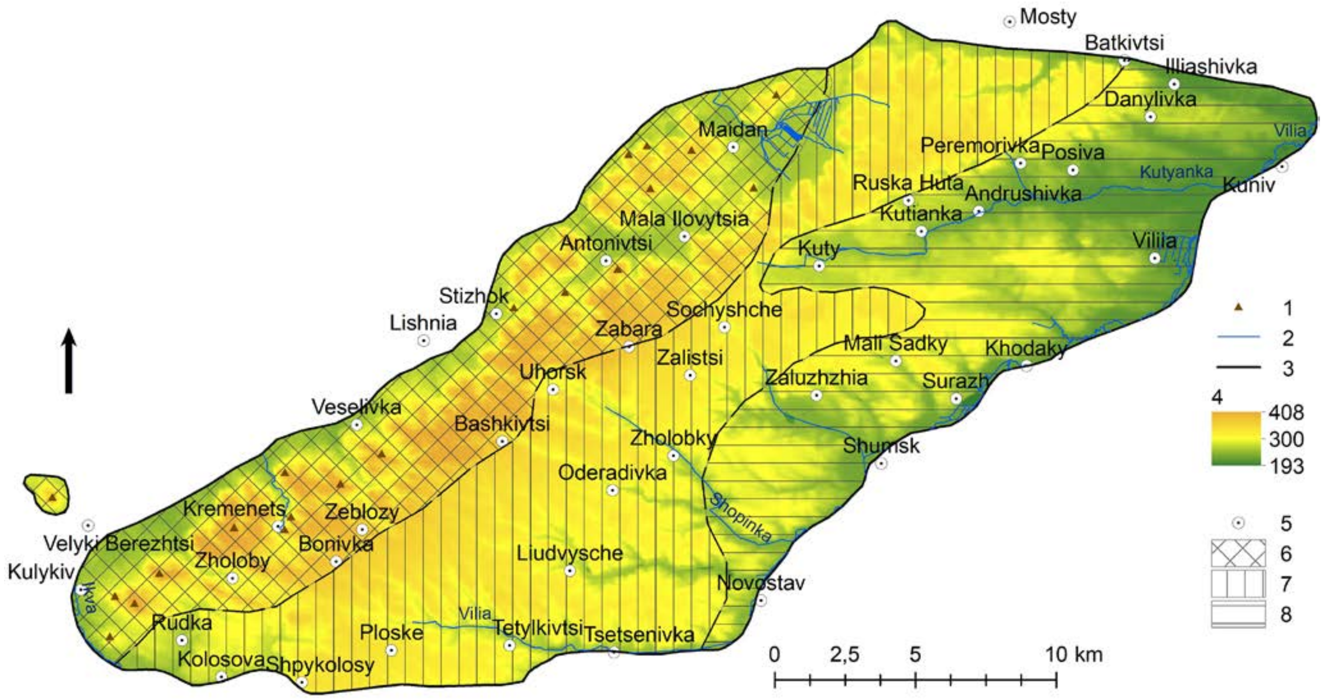

Fig. 12. Map of the geomorphological regionalisation of the Kremenets Mountains: 1 – main peaks, 2 – water bodies, 3 – boundaries of geomorphological subdistricts, 4 – elevation, m a.s.l., 5 – settlements. *Geomorphological subdistricts*: 6 – Kremenets steeply sloping highly dissected subdistrict, 7 – Zalistsi moderately sloping meanly dissected subdistrict, 8 – Kutianka gently sloping slightly dissected subdistrict.

tor, which combines the slope gradient, the density and the depth of the terrain dissection (Table 2).

The Kremenets steeply sloping highly dissected subdistrict includes escarpment areas and residual hills. The elevations are 390–408 m (Drabanykha Hill) and are the highest on the upland territory. The relative heights reach 80–100 m. High values characterise the slope gradient – there are slopes steeper than 20°. Also, the highest values of the depth of dissection (vertical dissection) are found here – the indicator ranges from 30 to 90 m/km^2. The density of dissection (horizontal dissection) differs within the subdistrict – in its southwestern part, the indicators are close to the average value in the upland and are 1–2 km/km^2, and in the northern part of the subdistrict, the highest indicators in the Kremenets Mountains are observed here – 2.3 km/km^2. This subdistrict is characterised by denudation and erosion-accumulation landforms and partly by karst and gravity ones, namely residual hills and a dense network of gullies that cut the escarpment of the Kremenets Mountains. Steeply sloping surfaces, sometimes with outcrops of the Cretaceous marls, and the Neogene sandstones and limestones are typical for the residual hills. Morphologically, the tops of the residual hills have a plateau-like surface (flat), except for Stizhok Mount, which has a dome-shaped summit (Fig. 13). The residual hills within the selected subdistrict are characterised by some differences in hypsometric position, in particular, the western group of mounds has a higher hypsometric level (380–408 m) than the similar ones of the northern group (330–360 m). Some differences can also be observed in the gullies and dry-valley networks. The northern part has a denser structure and more significant branching of this network, in contrast to the western part of the selected subdistrict of the Kremenets Upland.

The Zalistsi moderately sloping meanly dissected subdistrict is characterised by elevations ranging from 310 to 350 meters. Some areas have relative heights that can reach up to 20–40 meters. The subdistrict is characterised by a combination of structural-denudation and fluvial landforms, with some karst formations. Among the fluvial ones, dry valleys prevail, in some places with a branched gully network. Karst forms are represented by sinkholes that are spread over almost the entire territory of the subdistrict. The main morphometric indicators have average values for the territory of the upland. Slopes are characterised by moderately sloping indicators of steepness, namely 5–8°. However, on the northern escarpment in the Zbytenka River basin, the slope gradient occasionally exceeds 10°. The average values of the main morphometric

Table 2. Morphometric characteristics of the subdistricts of the Kremenets Mountains.

Subdistricts	Slope gradient [°]	Depth of the terrain dissection [m/km²]	Density of the terrain dissection [km/km²]
Kremenets subdistrict	>20°	30–90	1.5–2.0
Zalistsi subdistrict	5–20°	40–60	1.1–1.3
Kutianka subdistrict	<10°	20–40	1.8–2.0

Fig. 13. The residual hill of Stizhok.

indicators for the upland territory are 40–60 m/km^2 for vertical dissection of the relief and 1.0–1.3 km/km^2 for horizontal dissection of the relief.

The Kutianka gently sloping slightly dissected subdistrict is characterised by the dominance of fluvial landforms, in particular, floodplain and terrace complexes, and a branched dry valley network. The lowest indicators of absolute and relative heights on the upland territory are concentrated here. The highest absolute height values in this subregion are up to 280 m, and the maximum relative heights range from 10 to 20 m. The slope gradient is defined as gently sloping, with a maximum value of 5.8°. The depth of relief dissection is characterised by indicators of 20–40 m/km^2, only in some places, it exceeds 50 m/km^2. Instead, the value of the density of dissection in this subdistrict differs from the rest of the indicators, and it is represented by parameters higher than the average for the entire territory of the Kremenets Mountains – 1.8–2.0 km/km^2 and higher.

CONCLUSIONS

The Kremenets Mountains are still poorly studied in terms of geomorphology. Automatic morphological classifications of the relief, such as geomorphons and the topographic position index, reflect the main morphological features, particularly, clear boundaries of terrain types and approximate boundaries of landforms. When correlating the obtained results with the geological maps of bedrock and superficial Quaternary sediments, the geomorphological structure of the Kremenets Mountains was characterised. As a result, the following types of relief were distinguished: structural and denudational, denudational, fluvial, and also, based on our field research, gravitational, karst, biogenic, and technogenic landforms. It should be noted that the relief forms have a more generalised classification and require further study.

The main morphometric indicators in the territory of the Kremenets Mountains reflected certain patterns in the distribution of high, mean and low indexes of each. Maps of the main morphometric indicators were constructed and characterised in equal squares of 1×1 km, namely slope gradient, horizontal (density) and vertical (depth) dissection of the relief. The slope gradient is characterised by significant values over the territory of the upland, in particular, the maximum at 23°. Vertical dissection is marked by high indexes along the escarpment and on the areas of the residual hills, and high values indicate horizontal dissection in the central and eastern parts of the upland, where permanent watercourses form the most extensive network.

There are numerous problems in the issue of geomorphological regionalisation of the Kremenets Mountains, in particular:

- segregation of the Kremenets Mountains into a separate taxon;
- its more detailed division based on the selected landforms, as well as morphological and morphometric features of the relief;
- assigning a territorial affiliation to the residual hill, better known as the Bozha Hill: allocating it to the subregion of the Male Polissia lowland or determining its structural and geological characteristics to assign it to the territory of the Kremenets Mountains, etc.

During the geomorphological regionalisation of the Kremenets Mountains, geomorphological subdistricts are distinguished based on the specific features of the morphometry and morphology of the relief. Based on the conducted research, the allocation of geomorphological subregions within the Kremenets Mountains was justified, namely the Kremenets steeply sloping highly dissected subdistrict, the Zalistsi moderately sloping meanly dissected subdistrict, and the Kutianka gently sloping slightly dissected subdistrict.

As a result of our research, the Kremenets Mountains limits were specified, the main features of their relief were studied, and, as a consequence of this, geomorphological regionalisation was carried out. All this gives grounds to assert that the Kremenets Mountains are a separate geomorphological region of the Podolian Upland.

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Conflicts of interest

The authors declare no conflicts of interest.

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