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AUTOMATED ECOLOGICAL TERRAIN MORPHOLOGY CLASSIFICATION OF STRETCH OF UPPER DNISTER RIVER VALLEY

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Abstract. Modern technological developments can induce substantial changes not only in research methods, but also in theoretical concepts and approaches in Earth sciences. Recent developments in the technologies of remote sensing, GIS data processing and mapping now make possible to more directly consider ecologically relevant properties in the process of spatial units delineation. The concept of morphotop has been proposed by author meaning spatial units mapped taking into account ecologically relevant properties of terrain. It is different from the commonly used concept of natural complex in that ecological and not genetic criteria are at the base of spatial units differentiation.

The ecological approach for terrain morphology classification has been applied for the 4.5 to 2 km study area located at the upper part of Dnister river valley. The 10 m spatial resolution DEM was obtained for the study area by the interpolation of digitized topographic map layers with ANUDEM algorithm. Three groups of ecologically meaningful factors of landscape differentiation have been taken into account: 1) solar radiation redistribution; 2) water and soil moisture redistribution; 3) erosion potential of terrain. For each of these, the appropriate index was proposed and derived from DEM by the respective formula. The method of iterative cluster analysis with ISODATA algorithm has been applied to these variables complemented with absolute elevation. This method distinguishes a predefined number of classes by revealing the natural groupings of data in attribute space. Arbitrary presetting the number of classes allows to classify data with the different levels of detail and to analyze the changes in classification output as a function of classification scale and detalization.

The study area has been successively classified into 12 and 8 classes, with 100 algorithm iteration in each case. Each class has been given a descriptive characteristic; an average values of certain terrain morphometric parameters for each class were also calculated and given in a table. The map of the distribution of the distinguished classes was produced.

Key words: terrain morphology, unsupervised classification, morphotop, ecological geomorphology

АВТОМАТИЗОВАНА ЕКОЛОГО-МОРФОМЕТРИЧНА КЛАСИФІКАЦІЯ ДІЛЯНКИ БАСЕЙНУ ВЕРХНЬОЇ ТЕЧІЇ Р. ДНІСТЕР

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Анотація. Розвиток сучасних технологій може зумовити зміни не лише у методах досліджень, але й у теоретичних концепціях та підходах в науках про Землю. Новітній розвиток технологій дистанційного зондування Землі, ГІС-технологій обробки даних та картування уможливлює більш пряме і точне врахування екологічно значимих властивостей під час виділення та картування просторових одиниць. Автором запропонована концепція морфотопів як просторових одиниць, картування яких здійснюється на основі безпосереднього врахування екологічно значимих властивостей рельєфу. Ця концепція відрізняється від поширеної концепції природних територіальних комплексів тим, що в основі виділення просторових одиниць лежать не генетичні, а екологічні критерії.

В даному дослідженні екологічний підхід до класифікації морфології рельєфу було застосовано для ділянки розмірами 4,5×2 км, розташованої у басейні верхньої течії р. Дністер. ЦМР дослідної ділянки з просторовою роздільністю 10 м отримано шляхом інтерполяції шарів топокарти з використанням алгоритму ANUDEM. В дослідженні враховувались три групи екологічно значимих факторів ландшафтної диференціації: 1) перерозподіл рельєфом сонячної радіації, 2) перерозподіл води та ґрунтової вологи, 3) ерозійний потенціал рельєфу. Для кожної з них запропоновано окремі індекси, які обраховано за ЦМР за відповідними формулами. Далі для цих індексів доповнених значеннями абсолютних висот було застосовано метод ітераційного кластерного аналізу на основі алгоритму ISODATA. Цей метод дозволяє виділити попередньо визначену кількість класів шляхом виявлення природних поєднань даних у просторі атрибутів. Довільне задавання кількості класів дає змогу класифікувати дані з різним ступенем детальності та аналізувати зміни в результатах класифікації як функцію її масштабу та деталізації.

Дослідну ділянку було послідовно класифіковано на 12 та 8 класів, в кожному випадку використовуючи 100 ітерацій алгоритму. Для кожного виділеного класу було наведено описову характеристику та обраховано середні значення кількісних морфометричних параметрів. Також складено карту просторового розподілу виділених класів по території дослідження.

Ключові слова: морфологія рельєфу, некерована класифікація, морфотоп, екологічна геоморфологія.

Introduction. Terrain morphology is an important factor of the spatial differentiation of biophysical and soil characteristics. It is thus one of the main criteria for the terrestrial ecosystem units delineation and mapping, by means of either manual and semi-automated or fully automated methods. It is claimed that boundaries between potential ecosystems can be mapped to coincide with changes in those landform characteristics known to regulate the reception and retention of energy and water (Rowe, 1996). Terrain morphometric parameters are also widely used for the purpose of soil mapping, especially when modeling and mapping the soil attributes connected with the gravitational redistribution of soil water, particles and nutrients.

While nowadays terrain morphometric parameters are often directly used to analyze and predict the distribution of climate, vegetation, ecosystem and soil characteristics (Gessler et al., 1995), (Gessler et al., 2000), (Syssouev, 2004), (Mkrtchian, 2016 a), the more traditional approach of delineating discrete spatial entities (units) comprising a distinctive pattern of landscape characteristics (encompassing characteristics of terrain, rocks, soils, climate, hydrology, plant and animal communities) remains appropriate. This approach has some important advantages, namely it is more intuitively comprehensible by decision makers who could operate on a limited set of strictly defined and mapped spatial units; these units are easily visualized on maps, their descriptive characteristics given in compact tabular form; these units can serve a basis for environmental stratification that provides sampling efficiency as it enables the precision of the estimates based on smaller samples and allows the results to be quantified with statistical descriptions of confidence (Jongman et al., 2006). Environmental stratification can thus serve as a stratification framework for monitoring biodiversity and habitats and as a framework for scenario building and reporting.

The traditional landscape science as it developed and proceeded in former USSR and post-Soviet countries has set as its ultimate task the comprehensive mapping and characterization of spatial entities denominated as “natural areal complexes” (Isachenko, 1991). These in fact are mostly the geomorphic spatial entities – landforms of different rank, their elements, and the complexes (patterns) of landforms, with the characteristics of other landscape components (soils, local climate, water regime, plant communities) being mechanistically bound to these entities under the hypothesis of unidirectional impact of geology and terrain properties on other components of landscape. This approach made a certain practical sense under the former conditions of the scarcity of detailed spatial data represented mostly by topographic maps and air photos, interpreted manually by experts. Yet the hypothetical model of the spatially discrete and strictly unidirectional relationships between landscape components is too unrealistic and goes against the dominant modern concepts of ecological and environmental sciences. Still another shortcoming lies in the fact that spatial units in geomorphology and landscape science are mostly delineated by the considerations of their genetic integrity, yet there is no one-too-one correspondence between genesis, modern dynamics and the ecological properties of these units. The genetically holistic spatial entity (unit) could have very dissimilar ecological properties in its different parts, and very similar ecological properties could characterize the units of completely different genesis.

Morphotops as units of automated ecological terrain classification. The rapid development of modern technologies of remote sensing utilizing the capabilities of satellite platforms to obtain detailed spatial data on various properties of land surface, land cover and natural environment, as well as the capabilities of modern GIS and spatial analysis technologies to rapidly process large amounts of data allow to model the relationships between the terrain and ecological characteristics in a more refined and realistic manner. Specifically, it is now possible to delineate spatial units directly on the basis of the properties relevant to ecological communities, as well as to human ecology, vital and economic activities.

The concept of morphotop has been proposed by us as an alternative theoretical basis for such an approach (Mkrtchian, 2004). Morphotop has been defined as an area with distinct land morphology and a certain degree of ecological homogeneity, sufficient enough for a given goal (e.g., land use or conservation planning and regulations) (Mkrtchian, 2004). Morphotopes can have different spatial dimensions depending on the degree of ecological homogeneity required, and can even have a nested structure. What distinguishes them from natural areal complexes and similar concepts prevalent in landscape science is that their delineation should explicitly take into account those properties of terrain that either influence of indicate the ecological conditions and properties relevant to them, like the redistribution of solar radiation on slopes of different aspect and the surface and subsurface movement of water and dissolved soil nutrients by the force of gravity.

An example of such an approach is our attempt at ecological classification of a small fluvially dissected forested area near Lviv, where five morphotopes have been delineated with ISODATA algorithm on the basis of ecologically meaningful indices characterizing the processes of solar radiation influx, water redistribution, and soil sheet-and-rill erosion (Kovalchuk & Mkrtchian, 2007). Analysis of variance then revealed significant statistically meaningful differences between these morphotops in terms of seminatural tree stand structure. In another our study, classification has been performed of 90×70 km area located in the central part of Ukrainian Carpathians using k-means method and a set of ecologically meaningful morphometric parameters (Mkrtchian, 2013). As this method allows to preset an arbitrary number of clusters, two different classifications were performed, respectively with 3 and 8 output clusters. These clusters were given an ecological interpretations; in fact they are two sets of morphotopes one being nested inside the other.

Methods of automated ecological terrain classification. Methods of ecological terrain classification form a continuum, from fully manual that totally depend on human expertise to semi-automated and automated, the latter deemed the most objective and reproducible, with the minimal possible contributions from human experts. Even manual methods nowadays often utilize the value of modern digital spatial data and GIS facilities for their preprocessing and visualization. Thus, I. Kruhlov delineated 33 morphogenic meso-ecoregions in Ukrainian Carpathians using GIS, grouping them together into five classes according to the geology features and also to nine bioclimatic classes according to their location respective to altitudinal bioclimatic belts (Kruhlov, 2008). While their direct spatial delimitation has been carried out manually, digital geospatial data were being used for the purpose of visualization, and further grouping of these units into higher-level classes has been obtained by means of hierarchical cluster analysis. In another work by I. Kruhlov, geoecological spatial units of different ranks were distinguished in the upper Western Bug basin using the combination of manual and semi-automatic methods, the latter used for distinguishing the lowest-rank units in the dissected part of the watershed by the classification with pre-defined value ranges of the two morphometric parameters derived from SRTM Digital elevation model (DEM) (Kruhlov, 2015).

During last decades, several attempts have been made at landscape classifications and mapping using modern remote sensing data and statistical methods of their processing, like cluster analysis and principal component analysis (PCA). On the large regional level, the works of (Metzger et al., 2005) and (Jongman et al., 2006) can be mentioned that attempt at the statistical environmental stratification of Europe. The final stratification consists of 84 strata aggregated into 13 Environmental Zones (Metzger et al., 2005). While it was based mainly on climatic data, altitude and slope were also taken into account. Detailed climatic surfaces in turn are usually produced taking into consideration relevant terrain parameters (Jarvis & Stuart, 2001), (Mkrtchian, 2016 a).

Among the studies encompassing smaller spatial scales, the typology of natural landscapes of Central Europe can be mentioned created with a non-hierarchical k-means cluster analysis using terrain variables together with climate and soils data; seven clusters were identified, interpreted as seven types of natural landscape and mapped with 10×10 km grid (Fňukalová & Romportl, 2014). Burrough et al. applied an unsupervised fuzzy k-means classification technique to eight topoclimatic attributes computed from a DEM for a 10 000 km^2 study area in the West Yellowstone National Park, which enabled to automatically extract a number of topoclimatic classes; specifically: valley bottoms, drainage channels, lower slopes, ridges, north-facing steep slopes, south-facing steep slopes and lakes (Burrough et al., 2001).

The concept of geometric signature plays a central role in the characterization of a link between quantitative terrain variables (features) and the holistic spatial entities (units) serving as an aim of classification. R. Pike defined the geometric signature as ‘‘a set of measures that describe topographic form well enough to distinguish among geomorphically disparate landscapes’’ (Pike, 1988). This is likened to ‘‘topographic fingerprint’’ that can apply to both individual landforms (watersheds, drumlins, landslides) and to composites of related landforms referred to as landscapes (Pike, 1988), (MacMillan, Keith Jones & McNabb, 2004).Whereas no single magic number or measurement exists that can express topographic character completely enough to be sufficient for unambiguous geomorphic interpretation, land topography is intrinsically synthetic and multivariate in nature. Its characterization is thus should be considered a statistical problem that requires a statistical approach and methodology (Pike, 1988), (MacMillan, Keith Jones & McNabb, 2004).

The problem comes up of the set of parameters (features) that comprise the geometric signature for the purpose of ecological terrain morphology classification. Simple terrain parameters like absolute elevation and slope values, their range and dispersion in a local window, and a system of local curvatures are most often used for this aim, mainly for the reason of the simplicity of their calculation in popular GIS-software. Yet for the derived classification to be ecologically meaningful, these parameters should in their turn carry an ecological meaning, being indicative of important ecological processes and properties of land surface. Thus, V. Syssouev used for the purpose of the landscape terrain classification three groups of topographic parameters characterizing respectively redistribution of solar radiation, redistribution of moisture and redistribution of solid matter under the influence of gravity (Syssouev, 2004). Our earlier works (Kovalchuk, Mkrtchian, 2007), (Mkrtchian, 2013) likewise used ecological meaningful topographic parameters for the purpose of delineation of ecologically homogeneous elements of terrain (morphotops).

Study area and input data. In our present work the ecological approach for terrain morphology classification has been applied for the 4.5 to 2 km study area located at the upper part of Dnister river valley. It encompasses the river floodplain, terraces and adjacent slopes, with the elevation range 370–670 m. The most detailed 1:10 000 topographic map was used as a source of terrain data. Digitized data containing elevation contours, points, streams, and water bodies were interpolated using ANUDEM algorithm, developed by M. Hutchinson (Hutchinson, 1989) and realized in ArcGIS software package with Topo to Raster tool and with TOPOGRID function in early versions of Arc/Info. Thus DEM was obtained for the study area with 10 m spatial resolution, which is substantially higher than the maximal solution of SRTM DEM (1-arc second ≈ 30 meters) and other freely available global DEMs.

Classification criteria and algorithm. Upon the examination of data, the river floodplain was excluded from the analysis because of its very complicated and highly dynamic relief, with even small variations in elevation often indicating very large differences in deposits composition, soils and water regime. Three groups of the factors of landscape differentiation being regulated by terrain have been taken into account: 1) solar radiation redistribution on surfaces of different aspects and slope angles; 2) water and soil moisture redistribution on watershed surfaces; 3) erosion potential that determines the energy of surface flow that regulates the erosion and deposition of solid matter.

To calculate the index that characterizes the solar radiation redistribution, the method based on the hemispherical viewshed algorithm developed by Fu and Rich was used (Fu & Rich, 2000). It calculates the integral amount of global insolation (as a sum of direct and diffuse ones) for the arbitrary time span, taking into account the effects of shading and the atmospheric absorption of radiation, but not taking into account its absorption by clouds and long-wavelength radiation. This method is realized through the Area Solar Radiation tool from the Spatial Analyst toolbox of ArcGIS Desktop GIS software. It allows to calculate the integral amount of global insolation for the arbitrary time span. The same kind of analysis can be performed with the Potential Incoming Solar radiation tool from the Terrain Analysis toolbox of the free and open-source SAGA GIS.

The total amount of potential incident solar radiation was calculated with this method for the most ecologically important time period from 1-st of March to 15-th of October. The histogram of the distribution of this value on the terrain is characterized by expressed asymmetry: the minimal values on the most shaded slopes of north aspect amount to only 35% of the values on crests and mountaintops and 38% from the average for the area. On the other hand, the minimal values on the sharp slopes of southern aspect exceed the latter values only by 10% and 15%, respectively. The incident radiation on the flat Dnister valley bottom appeared to be 3–5% less than on flat elevated surfaces due to shading effects from surrounding slopes.

The moisture redistribution under the force of gravity can be modeled by Topographic wetness index (*TWI*) suggested by (Moore, 1993). This index reveals the location of site in the landscape catena and is calculated by formula:

$$TWI = \ln(A_s / \tan\beta),$$

where A_s – drainage (flow accumulation) area per contour line unit length, β – slope angle. Large values of this index indicate the prevailing accumulation of water and its increased content in soil that influence physical-chemical soil characteristics, its microclimate, and in sum – the ecological characteristics of the site. A lot of studies use this index for the prediction of soil characteristics. The authors of (Gessler et al., 1995) have developed a statistical soil-landscape model for the prediction of soil characteristics using *TWI* among a set of morphological characteristics. It was shown that *TWI* alone can predict up to 71% of variation in the depth of the soil A horizon, 84% of variation in the total depth of soil profile, and 78% of the variation of soil carbon content (Gessler et al., 2000). This index can be calculated through a combination of Slope, Flow Accumulation, and Raster Calculator tools from the Spatial Analyst toolbox of ArcGIS. In SAGA GIS, it can be calculated directly through the Topographic Wetness Index tool from the Terrain Analysis toolbox.

On the our study area *TWI* values range from 0.5–1 on narrow convex crests to 5–10 in the lower parts of stream valley bottoms. Statistical distribution of these values is approximately normal, with average value ≈ 3.

To characterize the erosion potential of terrain, an equation from the Revised universal soil loss equation has been used:

$$LS = (m+1)\ [A_s / a_0]^m\ [\sin\beta / b_0]^n,$$

where A_s – drainage area per contour line unit length; β – slope angle; m and n – standard parameters; a_0 = 22.1м – the length and $b_0 = 0.09 = \sin(5.16^\circ)$ – the slope of standard plots, where the parameters of the model have been determined (Mitasova et al., 1996). While for the assessment of the real volumes of soil washout the values of *LS* index should be multiplied by the values of the other erosion factors (precipitation erosivity, soil and vegetation cover resistance to erosion and protective capacity), it alone characterizes the property of local terrain to conduce or counter soil erosion.

On the our study area the values of *LS* index were in the range from 0–1 at the level summits, flat terrace surfaces and valley bottoms to 50 and more at the steep lower parts of the slopes and at the heads and slopes of gullies.

The method of iterative cluster analysis has been employed for the purpose of ecological terrain morphology classification and morphotopes delineation. The classes are thus being automatically distinguished and delineated from the analysis of natural groupings of data in attribute space. Three above-mentioned ecologically meaningful indices were complemented with absolute elevation that accounts for climatic vertical temperature gradient and also helps in distinguishing between low-lying sites at the valley bottoms and sites at level summit surfaces that can otherwise have a similar insolation regime and similar values of *TWI* and *LS* indices due to low values of *ß* (slope angle). Before the classification all the indices were standardized by the subtraction of mean values and subsequent division to standard deviation of each index.

Isodata clustering algorithm realized in ArcGIS tool Iso Cluster (or old Arc/Info function ISOCLUSTER) is based on the principle of migrating averages. On every iteration each site (approximated by raster pixel) is attributed to the class with the closest centroid in the multivariate attribute space, whereupon the locations of each class centroids are recalculated and the algorithm proceeds to the next iteration; the process continues for the fixed number of iterations or until no change in classes is observed after the next iteration. The algorithm requires the number of clusters to be given beforehand, allowing to classify data with the different levels of detail and to analyze the changes in classification output as a function of classification scale and detalization.

Isodata clustering algorithm thus determines the characteristics of the natural groupings of cells in multidimensional attribute space and stores the results in an output ASCII signature file, that subsequently is used as the input for a classification tool, such as Maximum Likelihood Classification, that produces an unsupervised classification raster. In SAGA GIS this method is realized through the ISODATA Clustering for Grids tool from the Imagery toolbox. The more sophisticated algorithm implemented here allows the number of clusters to be automatically adjusted during the iteration by merging similar clusters and splitting clusters with large standard deviations (Memarsadeghi et al., 2007).

Results and discussion. The study area has been successively classified into 12 and 8 classes, with 100 algorithm iteration in each case. The most detailed classification, as expected, was obtained with 12 classes. In this case class 1 corresponds to river valley bottoms; class 2 – to lower terraces, also including gentle lower valley slopes; class 3 – to gentle and declivous lower slopes with "warm" southern aspects; class 4 – to declivous and steep lower slopes with "cold" northern aspects; classes 5 and 6 – to steep slopes of gulches, respectively of "warm" and "cold" aspects; class 7 – to declivous upper slopes, class 8 – to the steepest parts of gulches slopes, class 9 – to level summit surfaces and structural levels, class 10 – to declivous middle parts of slopes, class 11 – to steep upper slopes of "warm" aspects, class 12 – to steep parts of slopes at the tops of gulches. The bottoms of small erosion forms (gulches, ravines) were not classified properly.

When the number of classes was preset at eight, the new classes were obtained which still bear relations to the classes obtained earlier. Namely, the area of class 1 has substantially increased and now also encompassed gentle low slopes together with river valley bottoms. Class 2 has also somewhat increased its extent, retaining its essence. Class 3 now encompassed gentle and declivous lower slopes; class 4 – steep lower gulches slopes; classes 5 and 8 – steep upper and middle parts of slopes of, respectively, “cold” and “warm” aspects; class 6 – declivous lower slopes of “warm” aspects; class 7 – summit surfaces and gentle near-summit slopes.

The table gives average values of certain terrain morphometric parameters and ecologically relevant indices for the 8 distinguished classes. The picture shows the fragment of the map showing the location of some classes.

Table. Some average quantitative morphometric characteristics and indices for eight classes obtained

Class	Average slope, º	Average *LS* value	Average direct solar radiation incidence, MJ/m^2	Average *TWI* value
1	9.54	21.03	4045.8	3.52
2	7.92	4.95	4364.9	3.67
3	14.56	11.00	3863.2	3.12
4	24.59	24.91	3183.6	2.87
5	19.07	13.69	3603.0	2.63
6	14.34	12.87	4636.9	2.98
7	8.36	8.16	4509.1	2.86
8	20.96	21.63	4623.2	3.39

It can be seen that obtained classes differ substantially by the average values of most parameters. The boundaries of classes obtained generally well agree with the visually assessed character of the area landscape. An exception is the narrow bottoms of gulches and small valleys which the present method appeares unable to distinguish. It can thus be hypothesized that these classes differ significantly with respect to specific properties of soils, moisture regime, microclimate, natural vegetation cover, predisposition to exogenous processes (erosion, landslides, landfalls), etc. However, to verify this claim and thus the validity of this classification approach and method, the obtained results should be compared with the data on concrete landscape and ecosystem properties, e.g. by the method of analysis of variance. Thus the prospective future researches should compare the results of this classification (and similar classifications for other areas) with concrete data on soils properties, on-site hydrologic and microclimatic measurements, the observations of the structure and functional properties of vegetation cover. The latter can be obtained for the extended areas through the analysis of detailed multispectral satellite imagery, e.g. the calculation of spectral indices that indicate some important functional properties of the upper tier of vegetation cover (Mkrtchian, 2016 b).

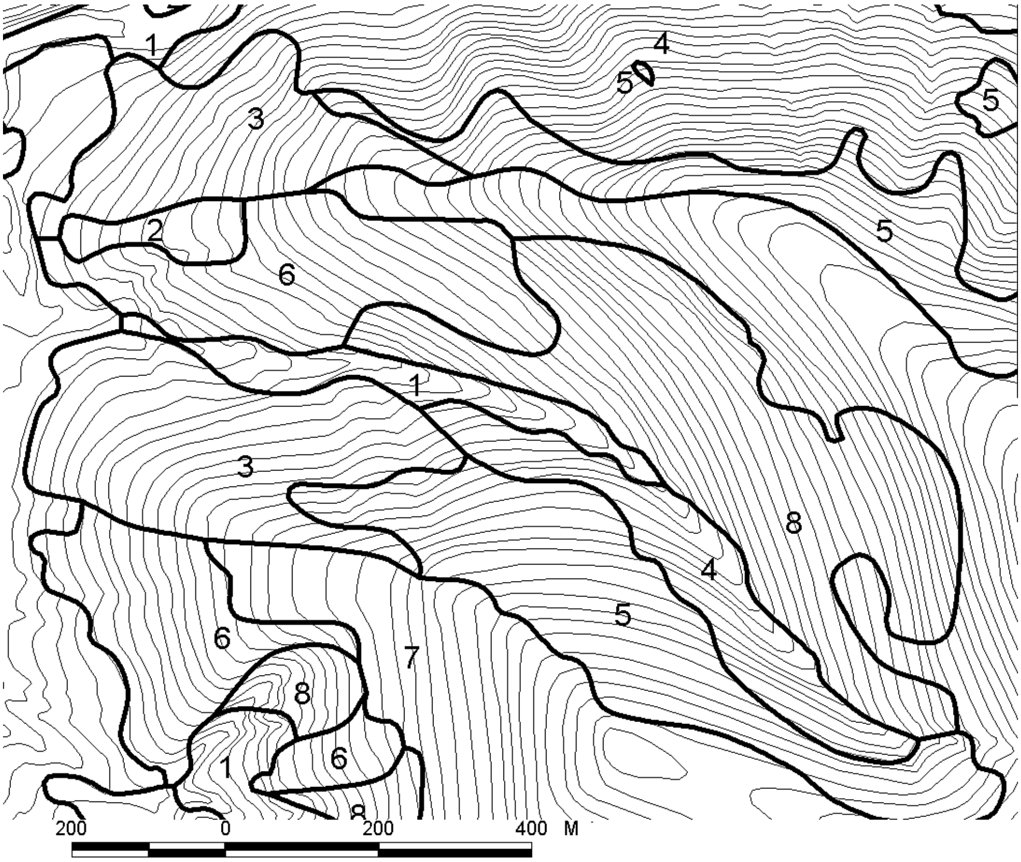

Figure. The fragment of map obtained for classification with 8 classes. Classes description see in text, some quantitative parameters see in Table.

Conclusions. Ecologically meaningful terrain morphology classifications are a promising method of ecologic geomorphology research that explicitly links terrain morphometric parameters to the ecological factors, habitat conditions, suitability of land for crops cultivation and other forms of economic activities, the quality of human environment. Modern data sources like DEMs and spatial imagery together with advanced tools of data processing offered by GIS and data analysis software present an opportunities to more directly take into account ecological requirements and factors while putting forward more appropriate conceptual models of landscape structure. New concepts like that of morphotop can serve the purpose to match the theoretical basis of landscape science and ecological geomorphology to modern data sources, data processing capabilities, and practical requirements. The most important avenue of future researches is the verification of classification principles and methods on the basis of concrete data on ecosystem structure and functioning.

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