UDC 551.4+911.2; DOI 10.30970/gpc.2024.2.4563

Hybrid delineation of landforms: Case of Bystrytsia-Pidbuzka drainage basin

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Abstract. Landforms, together with geological substrate and geomorphic processes, are essential for delineation of geoecosystems, which are indispensable for environmental management at landscape and regional levels. Geomorphometry is a geographic information system technology, which affords quantitative land-surface analysis and landform delineation using digital elevation models (DEM). Application of geomorphometry has been fostered by the emergence of free global high-resolution DEMs. However, automated geomorphometric extraction of landforms for flat areas, like wide river valleys, may be problematic owing to insufficient accuracy of the DEM.

We selected the Bystrytsia-Pidbuzka drainage basin of 500 km², which has a transitional location between low flysch External Carpathian Mountains and wavy denudation-alluvial plains of the Fore-Carpathian Upland in Lviv Oblast (Ukraine), to test a hybrid methodology of landform delineation – manual and automated geomorphometric. We considered regional landforms as orotectonic units (morphostructures), which are used to characterize ecoregions, and morpholithotopes as the smallest local landforms – mesorelief elements together with surface deposits and current geomorphic processes. FABDEM V1-2 with a resolution of 30*30 m was used as a primary geodataset of elevation data. Ecoregions and morpholithotopes of wide flat valley bottoms were delineated via manual interpretation of the DEM and ancillary data, while the morpholithotopes of the hilly and mountainous interfluves were delineated automatedly using three topographic variables: topographic position index, slope, and flow accumulation.

Within the study area, we singled-out six microecoregions and four mesoecoregions: Upper Dnister Depression, Upper Dnister Upland, Marginal Beskydy, and Dnister Beskydy. There are 21 classes of morpholithotopes distinguished belonging to flat valley bottoms with alluvial and lacustrine deposits, narrow valleys and big gullies, as well as lower concave and upper convex slopes formed by colluvial and eluvial-colluvial deposits respectively, divided into four inclination categories, and two lithological groups. Each morpholithotope class is attributed with a drainage status and probable current geomorphic processes. The obtained dataset is oriented on further ecological application.

Key words: morpholithotope; ecoregion; geomorphometry; FABDEM; the Carpathian Mountains; the Fore-Carpathian Upland.

Гібридне виділення форм рельєфу: приклад басейну річки Бистриця-Підбузька

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Анотація. Форми рельєфу, разом із геологічним субстратом і геоморфологічними процесами, є основою для делімітації геоекосистем, які застосовують для менеджменту довкілля на ландшафтному та регіональному рівнях. Тепер форми рельєфу усе частіше виділяють на підставі цифрових моделей висот (ЦМВ) за допомогою геоморфометрії – технології географічних інформаційних систем, спрямованої на кількісний аналіз рельєфу. Застосуванню геоморфометрії сприяє поява у вільному доступі глобальних високороздільних ЦМВ. Однак автоматизоване геоморфометричне виділення форм рельєфу пласких територій, таких як широкі річкові долини, може бути проблематичним через недостатню точність ЦМВ.

Ми вибрали басейн річки Бистриця-Підбузька площею 500 км², який займає пограничне положення між флішовими низькогір'ями Зовнішніх Карпат і хвилястими денудаційно-алювіальними рівнинами Передкарпатської височини у межах Львівської області, для тестування гібридної методики виділення форм рельєфу – мануальної й автоматизованої геоморфометричної. Для цього дослідили регіональні форми рельєфу як оротектонічні одиниці (морфоструктури), які використовують для характеристики екорегіонів, і морфолітотопи як найдрібніші локальні форми – елементи мезорельєфу разом із поверхневими відкладами та сучасними геоморфологічними процесами. ЦМВ FABDEM V1-2 із розділенням 30*30 м використали як основне джерело геоданих. Екорегіони та морфолітотопи широких пласких річкових долин виділили через мануальну інтерпретації ЦМВ та допоміжних даних, а морфолітотопи горбистих і гірських межиріч – автоматизовано з використанням трьох топографічних змінних: індексу топографічного положення, ухилу поверхні та показника акумуляції стоку.

У межах території дослідження виділили шість мікроекорегіонів та чотири мезоекорегіони: Верхньодністровську улоговину, Верхньодністровську височину, Крайові Бескиди та Дністерські Бескиди. Також розрізнили 21 клас морфолітотопів, які відображають пласкі днища долин з алювіальними та озерно-болотними відкладами, а також нижні увігнуті та верхні випуклі частини схилів з, відповідно, делювіальними та елювіально-делювіальними відкладами, які додатково поділені на чотири категорії ухилів поверхні та віднесені до двох літологічних груп. Кожен клас морфолітотопів охарактеризували з огляду на стан дренованості та ймовірні сучасні геоморфологічні процеси. Отриманий у такий спосіб набір геоданих орієнтований на подальше застосування в екологічних дослідженнях.

Ключові слова: морфолітотоп; екорегіон; геоморфометрія; FABDEM; Карпати; Передкарпатська височина.

Introduction. Landforms, together with geological substrate and geomorphic processes, are essential for delineation of geoecosystems (landscape ecosystems) – ecological systems with defined geospatial boundaries (Bastian et al., 2002; Kruhlov, 2020). The latter are indispensable for ecosystem-based management as a scientifically-substantiated sustainable environmental management (Landry et al., 2021). During last decades, traditional geomorphological mapping, which is based on field surveys and manual interpretation of contour maps and aerial/satellite images (Terrain…, 1997), has been extended with geomorphometry – a science and a geographic information system (GIS) technology of quantitative land-surface analysis and landform delineation using digital elevation models (DEM) and other ancillary data (Xiong et al., 2022). Sophisticated frameworks and different techniques, including special software, have been developed for automated delineation of landform elements and their characterization (Hopkins et al., 2024; Minár et al., 2024). Application of geomorphometry in regional-scale studies has been fostered by the emergence of free global high-resolution DEMs obtained via satellite optical and radar surveys (Meadows et al., 2024). However, automated delineation of landforms proves to be efficient and accurate mainly for mountainous and hilly terrain with pronounced topographic gradients (Xiong et al., 2022; Minár et al., 2024). For flat areas, like wide river valley bottoms, geomorphometric extraction of landforms may be more problematic owing to insufficient accuracy or noise (artefacts) of the DEM. Therefore, manual delineation of floodplains still may be preferred over automated procedures (Hopkins et al. 2024).

Hence, the goal of this study is to apply a hybrid (automated and manual) approach to the delineation and characterization of morpholithotopes – landform elements together with surface deposits and exogeneous processes – using a global DEM and collateral geodata and information. Also, we manually delineated regional landforms (morphostructures), which define spatial extents of ecoregions, using the same set of initial data / material. The Bystrytsia-Pidbuzka drainage basin was chosen as the model area owing to its heterogeneous mountain-plain transitional location, which causes diverse topographic gradients, geological substrates, and geomorphic processes within a relatively small area.

Study area. The Bystrytsia-Pidbuzka is a right tributary of the Dnister and its drainage basin is completely located in Lviv Oblast, Ukraine (see insert map in Fig. 2). The study area encompasses a river basin of 500 km² with a pour point at the confluence with the Tysmenytsia, and the length of the main channel is 79 km. The Bystrytsia-Pidbuzka and its left tributary the Cherkhava originate from the flysch low Carpathian Mountains. The middle and lower parts of the basin belong to wide valleys and wavy interfluves of the Upper Dnister Fore-Carpathian Upland. Altitude varies from 858 m (Vydilok Mnt) at the SW basin boundary to 255 m at the confluence with the Tysmenytsia in the E. The Carpathian interfluves are covered with eluvial-colluvial rocky loam – the regolith of sand-silt and sandstone flysch (shale), while the Fore-Carpathian interfluves are composed of colluvial (old alluvial) loam. The wide valley bottoms are filled with alluvial loam and lacustrine deposits (peat and silt), the floodplains and channels are of sand-pebbles in the upper flow and of loam in the lower flow (DHS, 2009; Transformation…, 2008).

According to the Köppen-Geiger climate classification, macroclimate of the drainage basin is of a Dfb type – cold, without dry season, and with warm summer (Peel et al., 2007). The nearest weather station (Drohobych, altitude 277 m) registered mean air temperature of -3.4°C for January and of +18.1°C for July, and annual precipitation amount of 744 mm (Shuber, 2018). Brown forest loam-scree soil (Dystric Cambisol) prevails on the interfluves of the mountainous part of the basin, while brownish-podzolic pseudogley soil (Staginc Albeluvisol) is typical for the wavy interfluves of the Fore-Carpathian plain. Valley bottoms are occupied by alluvial and boggy soils (Luvsiol, Fluvisol) as well as peat (Grunty…, 2019; Transformation…, 2008). Wetlands are mostly drained now, and natural forest cover is reduced. Natural ecosystems are substituted by agricultural fields, forest cultures, and villages. There is a hydropower plant in the lower flow, and the river channel is canalized and limited by dikes.

Conceptual framework. A morpholithotope is an elementary (non-divisible, relatively homogeneous) geographic area limited by a mesorelief element. Thus, the minimum size of a morpholithotope, as a geography-scale area (Haggett et al., 1965), is somewhat arbitrary, but it lies somewhere within the range of 0.1–10 ha (Kruhlov, 2020). A morpholithotope is characterized by the topographic position, geomorphometric indices, substrate (surface deposit) and geomorphodynamics –

exogeneous processes, which currently occur or may take place in case of a disturbance (e.g., landsliding that can be triggered by an extensive rainstorm). A morpholithotope can be also interpreted as two separate geoecological entities – a morphotope as an elementary landform of a geographical scale and a lithotope as an elementary geographical area of a surface deposit / soil parent rock. A morpholithotope, together with a climatope, hydrotope, and biotope, forms an elementary morphogenic geoecological unit – an ecotope (Bastian et al., 2002). Thus, morpholithotopes are essential for the delineation of ecotopes as elementary objects of ecosystem-based management. As small local landscape units that often have a recurring pattern, individual morpholithotopes are usually grouped into classes and are mapped as typological entities (Kruhlov, 2020).

Regional landforms (morphostructures) are macrorelief forms defined by the bedrock and neotectonics, and they have a spatial extent of over 10 km². From the standpoint of geoecology, morphostructures are interpreted as regional geoecosystems – ecoregions. In this case, geomorphic properties can be supplemented by the descriptions of other ecological components – climate, biota, and human population with artefacts. Ecoregions can be represented hierarchically as micro-, meso-, and microecoregions – depending on the spatial scale of morphostructures defining their boundaries. Unlike local landforms (morpholithotopes / ecotopes), regional landforms (morphostructures / ecoregions) are mostly mapped and described as individual units that bare unique names (Kruhlov, 2020).

Material and methods. The primary dataset used for the landform delineation was FABDEM V1-2, which is freely available for non-commercial projects (https://data.bris.ac.uk/data/dataset). It is based on a radar global Copernicus GLO 30 DEM with a ~30 m resolution at the equator (https://spacedata.copernicus.eu/collections/copernicus-digital-elevation-model), and is corrected for distortions caused by tree cover and buildings. Owing to the correction, the mean absolute vertical error was reduced from 1.62 m to 1.12 m for built-up areas, and from 5.15 m to 2.88 m for tree-covered areas (Hawker et al., 2022). Comparison with other global DEMs of a 30 m resolution – Copernicus DEM, NASADEM, AW3D30, and SRTM – shows superior accuracy of FABDEM, especially for tree-covered areas with low surface gradients (Meadows et al., 2024). We also used the official vector dataset of the river network of Ukraine (http://geoportal.davr.gov.ua) and a high-resolution composite satellite image provided by ESRI (https://services.arcgisonline.com/ArcGIS/rest/services/World_Imagery/MapServer). The medium-scale (1:200,000) official map of Quaternary deposits (DHS, 2009) was chosen as a collateral source of information about the geological substrate. We used ArcGIS Pro (https://pro.arcgis.com) and WhiteboxTools (https://www.whiteboxgeo.com) software to process the geodata, which were projected into UTM coordinates with a resolution of 30*30 m. The workflow is visualized in Fig. 1.

Vector data of the river network were rasterized and “deepened” into FABDEM by 2 m to ensure correct geometry of the channels, and a hydrologically-corrected DEM, which does not contain significant errors of flow accumulation, was produced. This DEM was used to automatedly derive the limits of the river basin and to obtain three other geodatasets: 1) slope (surface inclination), 2) topographic position index (TPI), and 3) network of watercourses with assigned Strahler ranks. Slope geodata were classified into four categories: 1) gentle slopes (0–5°), 2) moderate slopes (5–10°), 3) moderately steep slopes (10–20°), and 4) steep slopes (> 20°). TPI presents relative height of a location within a certain neighborhood (De Reu et al., 2013), which, in our case, had a circular form with a 300 m radius. Continuous TPI values were classified into two categories: 1) lower (concave) slopes (TPI =< 0) and 2) upper (convex) slopes (TPI > 0). Raster dataset of watercourses with assigned Strahler ranks was derived automatedly from the hydrologically-corrected DEM. We estimated empirically that a watercourse averagely initiates from a watershed area of ~10 ha (111 raster cells), and that watercourses of the second rank and higher form distinct valleys or gullies. Thus, we used watercourses of the second and higher rank to mark narrow valley bottoms or large gullies. The three categorical datasets (TPI, slope, and narrow valleys) were merged into a new synthetic dataset representing morphotopes of the interfluves. However, this dataset failed to realistically convey geomorphology of wide flat valley bottoms.

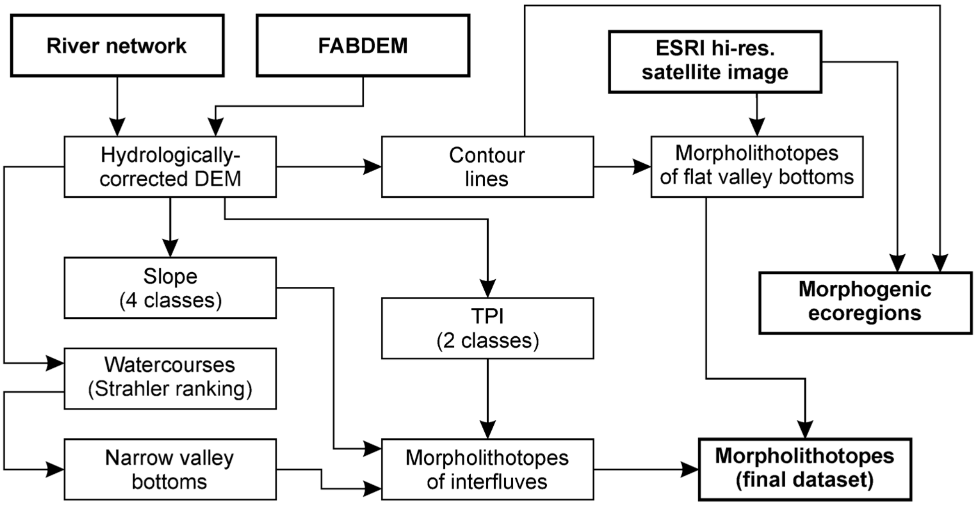

Fig. 1. Geodata processing workflow

Flat wide valley bottoms and boundaries of regional landforms (ecoregions) were delineated manually based on 5 m and 1 m contours generated from the DEM. The high-resolution satellite image provided additional information, especially for the separation of the floodplains from low terrace surfaces. The map of Quaternary deposits afforded to attribute the obtained polygons with basic information on surface deposits. The polygons were rasterized and merged with the dataset of the interfluve morphotopes. The final geodataset of morpholithotopes was filtered to eliminate isolated single cells – artefacts of classification and overlay operations. We used information from regional literature (Transformation…, 2008) to attribute each morpholithotope class with a list of probable exogeneous processes and to establish ranks of the ecoregions. For each ecoregion, area was calculated as well as mean altitude and mean slope values were obtained via zonal statistical overlay with the DEM.

Results and discussion. We delineated six microecoregions belonging to four mesoecoregions and two macroecoregions – the Fore-Carpathian Upland and the Outer Carpathian Mountains (Fig. 2, Table 1). The Fore-Carpathian Upland is represented by two rather contrasting mesoecoregions – the Upper Dnister Depression, which is a flat

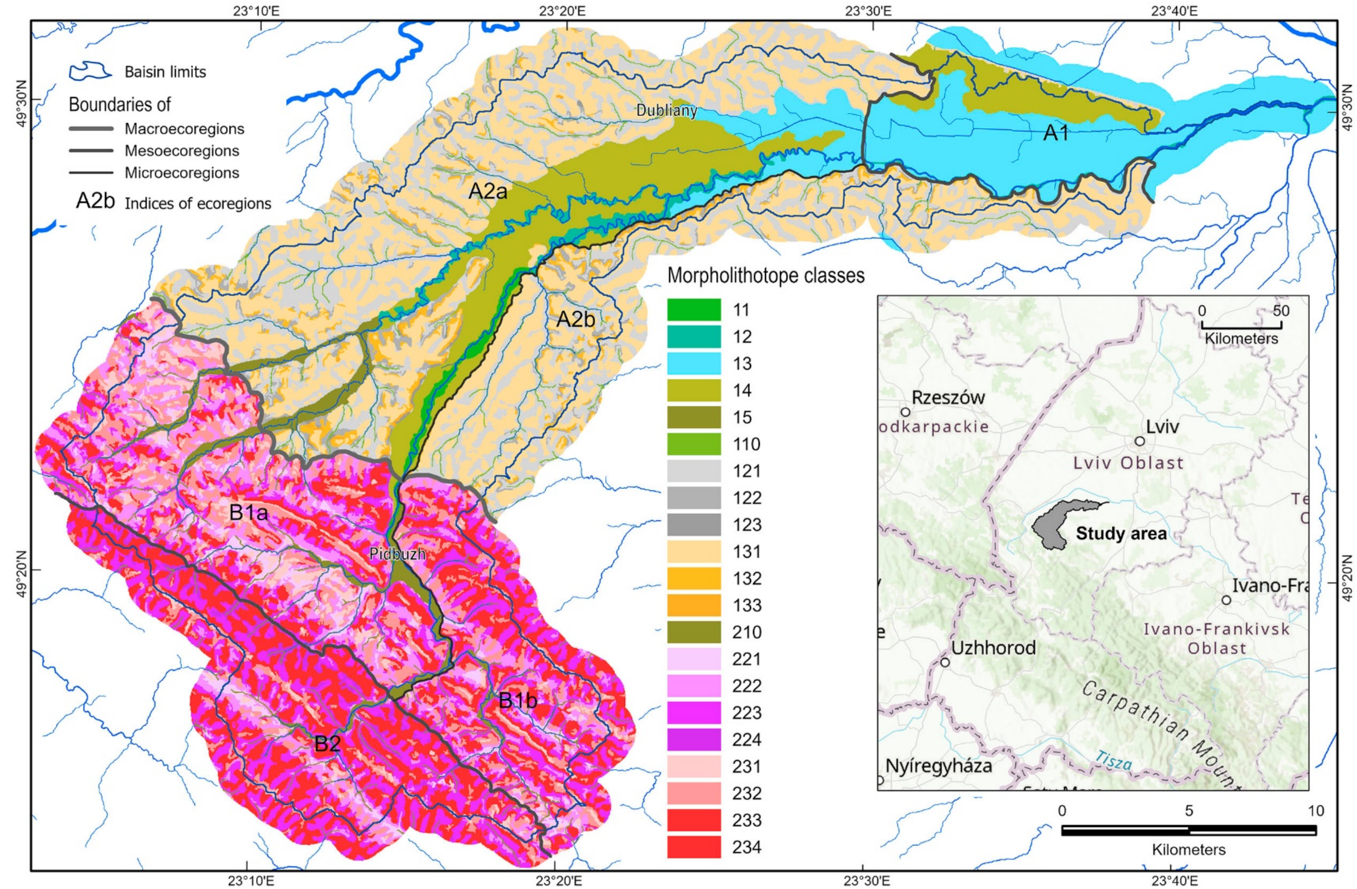

Fig. 2. Morphogenic ecoregions and morpholithotopes of the Bystrytsia-Pidbuzka basin. Descriptions are provided in Tables 1 and 2

alluvial-lacustrine plain with peat deposits, and the Upper Dnister Upland consisting of alternating wide river valleys and gently sloping interfluves. The latter are formed by bedrock silicious strata of the Carpathian Foredeep and are covered with old alluvium, which is overlaid modern colluvial loamy deposits. The Outer Carpathian Mountains are formed here by the Skyba (Skole) flysch nappe and contain two smaller geoecological units – the Marginal Beskydy and the Dnister Beskydy. Both fall into the same class of low flysch mountains, but the Dnister Beskydy, which are located closer to the mountain interior, are higher and have stronger vertical dissection manifested in larger mean slope values (see Table 1). This regionalization generally follows previous geomorphological (Kravchuk, 2021) and geoecological (Kruhlov et al., 2008; Mukha, 2003) schemes, but provides more accurate boundaries – as on a 1:50,000 map.

Table 1. Characteristics of morphogenic ecoregions (regional landforms) of the Bystrytsia-Pidbuzka basin (see Fig. 2)

Index	Area (ha)	Mesoecoregion name	Geomorphic class	ALT[1] (m)	SLP[2] (deg.)
A. Macroecoregion Fore-Carpathian Upland					
A1	4 270	Upper Dnister Depression	Flat alluvial-lacustrine plain	265	0.2
A2a, A2b	24 119	Upper Dnister Upland	Wavy denudation and alluvial plain	321	2
	B. Macroecoregion Outer Carpathian Mountains				
B1a, B1b	15 502	Marginal Beskydy	Low flysch mountains	510	9
B2	6 115	Dnister Beskydy		664	14

[1]ALT – mean altitude; [2]SLP – mean slope

There are 21 classes of morpholithotopes delineated within the study area (see Fig. 2, Fig. 3, 4; Table 2). They form two distinct groups: 1) flat alluvial valley bottoms (classes 11–15), which were delineated manually, and 2) interfluves with gentle–steep slopes (classes 110–234) generated automatedly. We distinguished two categories of floodplains: 1) formed by coarse material (pebbles, gravel, sand), which corresponds to the fast upper flow of the Bystrytsia-Pidbuzka with braided mountain-type channel (class 11), and 2) composed of sand and loam, which is typical for the Cherkhava and the Bystrytsia slower lower flow with meandering channels (class 12). We also separated low (2–5 m) terrace formed by alluvial loam (class 14) from the lower surface of a high floodplain–low terrace composed of alluvial and lacustrine mineral and organic deposits (class 13). The boundary between these two morpholithotope classes in some areas is rather arbitrary owing to very smooth transition, which cannot be revealed neither by the DEM, nor by the satellite image (see Fig. 3). Terraced valley bottoms (class 15) were delineated mainly in the mountains, where terraces and floodplains are too narrow to be presented as separate entities. Morpholithotopes of valley bottoms are usually poorly drained because of a shallow ground water table, and they are subject to flooding, waterlogging, and lateral erosion as typical current processes in these locations.

Morpholithotopes of the interfluves, which were delineated automatedly, are divided into two groups according to the geological substrate referring to: 1) eluvial-colluvial loam covering surfaces of old river terraces within the Upper Dnister Upland (classes

Table 2. Characteristics of morpholithotopes of the Bystrytsia-Pidbuzka basin (see Fig. 2)

Class index	Topographic position	Slope (deg.)	Surface deposits*	Drainage	Processes
11	Floodplain	0–1	Al pebble–sand	Very poor	Flooding, waterlogging, lateral erosion
12			Al sand – loam		
13	Floodplain – low terrace		Al sand – clay, Ln peat		Waterlogging
14	Low terrace		Al loam		
15	Terraced valley bottom		Al pebble – loam, Col loam		Flooding, waterlogging, lateral erosion
110	Narrow valley bottom		Al sand – clay		
121	Lower (concave) slope	1–5	Col loam	Poor	Material deposition, waterlogging
122		5–10		Poor-moderate	Material deposition, gully erosion
123		10–20		Moderate	Material deposition, gully erosion, creep, landsliding
131	Upper (convex) slope	1–5	El-col loam	Poor-moderate	Slight sheet erosion
132		5–10		Moderate	Moderate sheet erosion
133		10–20		Moderate-good	Moderate-strong sheet erosion, creep
210	V-shaped valley bottom	0–5	Al pebble – sand, Col rocky loam	Very poor	Flooding, waterlogging, lateral erosion
221	Lower (concave) slope	1–5	Col rocky loam	Poor	Material deposition, waterlogging
222		5–10		Poor-moderate	Material deposition, gully erosion
223		10–20		Moderate	Material deposition, gully erosion, creep, landsliding
224		> 20		Moderate-good	
231	Upper (convex) slope	1–5	El-col rocky loam	Poor-moderate	Slight sheet erosion
232		5–10		Moderate	Moderate sheet erosion
233		10–20		Moderate-good	Moderate-strong sheet erosion, creep
234		> 20		Good	Strong sheet erosion, creep

*Al – alluvial, Col – colluvial, El – eluvial, Ln – lacustrine

110–133) and 2) eluvial-colluvial rocky loam as a regolith of the flysch bedrock in the mountainous part of the river basin (classes 210–234). In each group, we distinguished narrow valley bottoms / big gullies (classes 110 and 210) as well as lower (concave) and upper (convex) slopes of several inclination categories. Slopes of the Upper Dnister Upland are mostly gentle (< 5°), and only at the close proximity to the mountain margin they sometimes exceed a 10° value. Slopes of the mountainous part of the basin usually exceed a 10° value (see Fig. 3 and 4), and in the Dnister Beskydy they are frequently steeper than 20° (see Fig. 2). Convex upper parts of the slopes are generally characterized by denudation, which form eluvial-colluvial type of the regolith, while concave lower parts of the slopes are more prone to accumulation and thus have purely colluvial type of the regolith. We predict fluvial (erosion) and gravitational (creep, landsliding) processes as typical for the interfluves, and their intensity increasing with the slope inclination (see Table 2). Slope position implies divergent (upper / convex slope) or convergent (lower / concave slope) mass movement, which allows prediction of the regolith and soil depth as well as their drainage status (Terrain…, 1997). The inclination category of a slope suggests georelief energy and thus intensity of geomorphic processes. For example, lower slopes are more prone to landsliding owing to deeper and wetter regolith than upper slopes; landsliding is more likely to occur on a steep slope than on a gentle slope owing to larger gravity vector (Mihai et al., 2014).

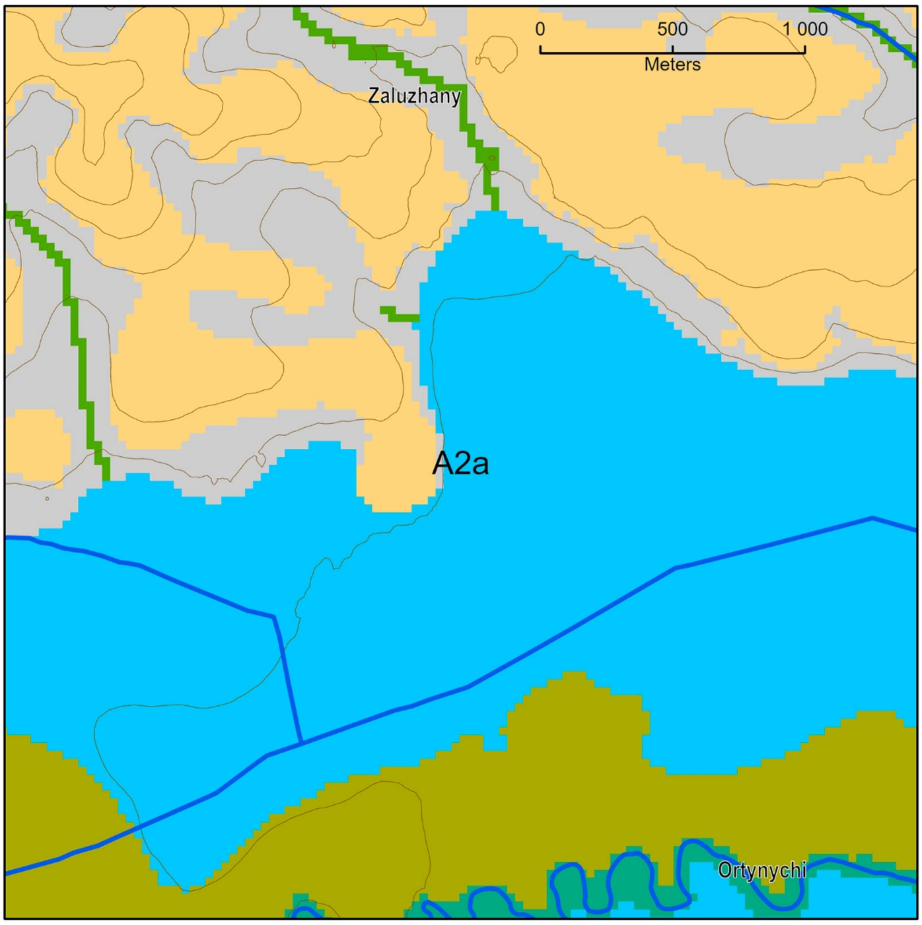

Fig. 3. Enlarged fragment of morpholithotopes geodataset for the plain part of the basin overlaid with 5 m contour lines. For legend see Fig. 2 and Table 2

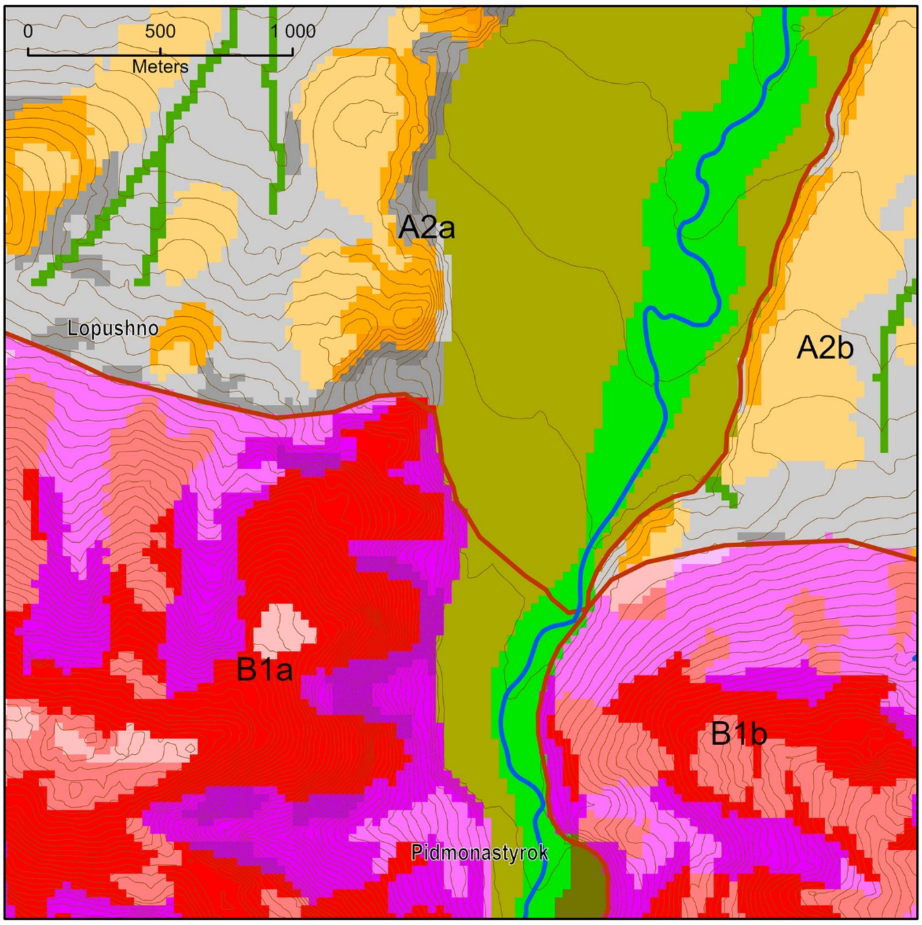

Fig. 4. Enlarged fragment of morpholithotopes geodataset for the mountain part of the basin overlaid with 5 m contour lines. For legend see Fig. 2 and Table 2

Our geodataset of morpholithotopes significantly differs from "classic" geomorphological maps and schemes, which concentrate on denudation / accumulation surfaces, their hypsometrical position, genesis, and age (Huhmann et al., 2004; Kravchuk, 2021; Yatsyshyn, 2016). Contrastingly, it pays more attention to geomorphometry and links geomorphometric parameters to surface deposits and current geomorphic processes. In this way, our dataset is more useful for further ecological interpretations. For example, if supplemented with climatic data, it can be used to predict potential natural vegetation and soil cover (Kruhlov, 2020), or, if supplemented with actual land-cover data, it can be used to characterise hydrotopes (hydrologic response units), which are essential for hydrological modelling of complex watersheds (Neitsch et al., 2011). The main drawback of our study is lack of empirical (field) material, which would afford quantitative probabilistic estimation of current geomorphic processes occurrence.

Conclusions. The Bystrytsia-Pidbuzka drainage basin has a diverse geological-geomorphological structure formed by flysch mountains with steep slopes as well as by wavy denudation-alluvial plains with gently-sloping interfluves and with wide flat valley bottoms. Therefore, the basin is a good model area for the development and testing of mapping approaches and techniques, which can be applied both for mountain and plain areas. Among such techniques, we made a special emphasis on geomorphometry as an automated method of landform delineation using DEM and derived topographic variables.

A global elevation dataset FABDEM of 30*30 m resolution turned out to be efficient for automated coarse-scale delineation of morpholithotopes of hilly and mountainous terrain using basic geomorphometric variables, such as TPI, slope, and flow accumulation. However, vertical accuracy and residual artefacts of elevation correction – removal of distortions caused mainly by tree cover – do not allow reliable delineation of landform elements within flat valley bottoms. Therefore, manual geomorphological interpretation of high-resolution satellite images and topographic contours remained a first-choice alternative for accurate mapping in flat areas.

The automated methodology proposed in this article aimed primarily at the delineation of morpholithotopes, their composition and processes, as principal components of elementary ecological landscape units – ecotopes. Thus, the methodology does not support delineation of denudation surfaces at different hypsometric levels, which are key objects of "traditional" geomorphological maps. Also, this study should be expanded by a field survey of current geomorphodynamics, which will afford for a quantitative estimation of the susceptibility of morpholithotopes to gravitational and erosional processes.

Acknowledgement. This study was done in the framework of the research project 0121U113567 supported by the Ministry of Education and Science of Ukraine.

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Стаття надійшла в редакцію 17.10.2024
Прийнято до друку 22.11.2024
Дата публікації 16.12.2024