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Intensity of relief geodynamic processes in the Coastal Lowland, Lithuania: based on cartographic analysis

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Abstract. The article overviews the indirect methods employed in assessing the intensity of geodynamic processes. These methods involve using and analysing various spatial topographic and thematic databases, including the databases of ortho-photo images, bogs and peatlands, CORINE land cover, crop fields, forest cadastre, flood-prone areas, the geomorphologic database, the database of relief cadastre as well as that of reclamation status and wet soils. In this study, the intensity of geodynamic processes was estimated using mathematical models, which include a number of factors behind surface transformation (accumulation/degradation) processes, i.e., the origin of the terrain, its morphographic and morphometric indicators, lithology, soil cover, the degree of sediment and soil wetness, and natural vegetation cover. In addition, the impact of the factors inhibiting surface erosion (ratio of clay and sand particles in the surface layer, slope inclination, humus content in soil, binary nature of soil-forming sediments) was evaluated. The cartographic analysis results were compared with the data obtained from the terrain investigation in key areas. The surface analysis based on the spatial distribution of geomorphological relief types, their roughness, land cover, forest, soil types, reclamation and soaked lands shows that weak deflation (up to 1 mm / year, 1214.8 km²), weak erosion (up to 1 mm / year, 367.1 km²) and medium biogenic accumulation (1–2 mm / year, 223.5 km²) are taking place in the Coastal Lowland.

Keywords: *cartographic analysis, accumulation, erosion, deflation, morphographic and morphometric indexes*

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INTRODUCTION

Natural (direct) research into geodynamic processes is complicated and expensive. In addition, it is difficult to perform measurements of geodynamic processes in slightly larger areas. The problem is usually solved either by conducting detailed surveys in reference areas and extrapolating the results obtained to a wider area, or by applying indirect measurement methods, one of which is the comprehensive analysis of the cartographic material. However, the cartographic approach to research always faces the problem of research scalability. The wider the analysed areas are, the more generalized data are used for analysis, and the more generalized measurement results are obtained. For a long time, the cartographic method was employed only when analysing the geodynamic processes that create relatively large (meso-rank) relief forms. The application of GIS and remote methods (LiDAR devices) allows collecting spatial information on small (micro-rank) terrain forms (Udin *et al*. 2012; Niethammer *et al*. 2011; Colomina, Molina 2014). On the other hand, extremely large volumes of information on surface dissections and roughness force researchers to look for optimal ways of information selection (Hu *et al*. 2014; Li 2013; Silván-Cárdenas, Wang L. 2006; Véga *et al.* 2012; Zhang *et al.* 2003; Smolska 2002). In Lithuania, the LiDAR methodology was applied for assessing the morphometric indicators of the Last and pre-Last Glaciations, i.e. marginal and insular moraine heights (Satkūnas *et al.* 2020).

For practical purposes, models of terrain changes and their causes should be the simplest possible (Zhang *et al*. 2003; Liu *et al*. 2012, 2015; Hu *et al.* 2009). It is best to single out a decisive (critical) component out of them, which reflects the state of the whole system. In our opinion, as soil is very sensitive to natural geomorphological or anthropogenic processes, it may be selected as such a component. Soil cover and its structure reflect local erosion-accumulation processes well. Research carried out in Lithuania shows a clear in-situ correlation between the structure of soil layers and erosion-accumulation processes (Račinskas 1990; Feiza *et al*. 2007; Jankauskas *et al.* 2008; Mažvila *et al*. 2010; Kinderiene, Karciauskiene 2016; Paškauskas, Vekeriotienė 2009).

The aim of this study was to evaluate the potential intensity of geomorphological processes in the Coastal Lowland (western part of Lithuania).

RESEARCH OBJECT AND AREA

The object of our study is the 30–40 km-wide Coastal Lowland, which is a territory of regional importance. In the south, the Coastal Lowland borders on the Highlands of Warmia (in Poland and in the Königsberg region of Russia), surrounds the Curonian Lagoon, and extends along the entire Baltic coast to the northern part of the Gulf of Rīga (to the Estonian territory). In the east, the Coastal Lowland borders on the Western Žemaičiai Plateau (on the territory of Lithuania) and the Kurzeme Upland (in Latvia). At the Gulf of Riga, the Coastal Lowland is surrounded by the Kurzeme Upland from north to east.

The eastern borderline of the Coastal Lowland coincides with the isoline representing the absolute height of 50 m. The relative heights of the lowland in its northern part, i.e., north of the Klaipėda – Gargždai – Endriejavas line, are the greatest, with the height of individual (non-river valleys) relief forms reaching10–15 m. Further away from this line, the relief is much smoother, with the height of separate relief forms varying between 5 and 10 m. South of the Saugos – Švėkšna line the relief is even more even, and the individual landforms reaching the relative height of 5 m are rare. The Coastal Lowland is divided by abundant river valleys, the relative heights of which are as follows: the Tenžė River valley – 15–20 m, that of the Danė-Akmena River – 15–20 m, the Minija River valley – 35–50 m, the Salantas River valley – 25–30 m, that of the Šventoji River – 10–15 m, the Bartuva River valley – 15–20 m, and the greatest relative height of the Erla River valley ranges between 12 and 15 m.

The Coastal Lowland consists of several segments: the Prieglius – Įsrutis River Lowland, the Nemunas Delta, and the Rīga Gulf Lowland. These lowlands formed during the glacial period, following the Baltic Ice Lake formation (17,000–11,700 cal BP) and during various stages of the Baltic Sea development: the Yoldia Sea (11,700–10,800 cal BP), the Ancylus Lake (10,800–9,800 cal BP) and the Littorina Sea (since 9,800 cal BP) (Bitinas 2011, Bitinas *et al.* 2000; Damušytė 2011, Damušytė *et al*. 2021; Hansson *et al*. 2019). Several relief levels, indicating the former water level, are distinguishable in the Coastal Lowland. The bright Baltic Glacial Lake level terrace is located north of Liepaja, elsewhere it merges with the relief formed by the glacier.

On the territory of Lithuania, the Coastal Lowland embraces the Baltic Coastal Plain, the Western Žemaičiai Plain and the Nemunas Delta. The Curonian Spit, which also belongs to the Coastal Lowland, is distinguished by aeolian dunes making its surface unique. The relative height of the highest Vecekrugas Dune is 67.2 m.

The relief of the Coastal Lowland is compounded of a number of relief types: flat sandy sea and alluvial terraces, glaciolacustrine plains, flat and undulating moraine and fluvioglacial plains, moraine ridges, isolated moraine hills and aeolian dunes. The surface of the coastal lowland is furrowed by glacier melting water valleys, through which the Minija, Danė-Akmena, Erla, Bartuva, and other rivers are flowing nowadays. The paleogeographical formation and river valley development in the southern part of the Coastal Lowland is described in detail in the article by A. Bitinas, A. Damušytė, M. Stančikaitė and P. Aleksa (Bitinas *et al*. 2002).

On the territory of Lithuania, several sections of moraine formations stand out in the relief of the Coastal Lowland: Kalotė end moraine and a chain of moraine arcs extending from Impiltis through Dimitravas, Rimkai, Lankupiai, Kintai towards Ventė Cape. In the south-eastern part of the Coastal Lowland, the ground moraine sediments are covered with glaciolacustrine deposits that accumulated in a slow-seated basin.

The slopes of the Minija-Erla valley were affected by intense erosion during the post-glacial period, and there are many gullies and ravines. At the beginning of the Holocene (10,700–8,300 cal BP), formation of the Pro-Nemunas delta began, which continues to this day (Bitinas *et al.* 2001, 2002; Damušytė *et al*. 2021). In the western part of the lowland, there are several distinct segments of littoral terraces. The widest ones near Palanga (2–3 km), and near the Olando Kepurė (the Dutchman's Cap) cliff have disappeared completely. South of Klaipėda, the boundaries of littoral terraces are difficult to trace: they were covered with alluvial deposits. In the southern part of the lowland, on the eastern shore of the Curonian Lagoon, in the shallow depressions of the relief, wetland formation processes and phytogenic accumulation take place. Typical bogs of Svencelė and Aukštumala have formed therein.

DATA SOURCES AND RESEARCH METODOLOGY

When assessing the potential intensity of geomorphological processes and determining their spatial coverage, we used the following cartographic databases:

1. Digital raster orthophoto map at scale 1:10 000 of the Republic of Lithuania 2018–2020 (ORT10LT), (2018–2020).
2. Bogs and peatlands of Lithuania at scale 1:10 000 (LGF 2018) (2018).
3. Copernicus Land – CORINE land cover at scale 1:10 000 (2018).
4. Spatial data set of the crop fields M 1:10 000 (2019).
5. Forest cadastre data at scale 1:10 000 (SŽNS_DR10LT) (2017).
6. Spatial data set of reclamation status and soaked soil of the territory of the Republic of Lithuania at scale 1:10 000 (Mel_DR10LT).
7. LIDAR data of flood-prone areas at scale 1:10 000 (2014).
8. Lithuanian geomorphological map at scale 1: 200 000 (2014).
9. Cadastre of Lithuania relief at scale 1:25 000 (2002).

Some of the data (soil granulometric composition and soil moisture) used in this study were obtained from the Spatial data set of soil of the territory of the Republic of Lithuania at scale 1:10 000 (Dirv_DR10LT) (2014).

For the assessment of geodynamic processes, we used a number of criteria describing the surface condition. They are as follows: the origin of the relief, its morphographic and morphometric indices, surface sediment cover, soil cover, the degree of sediment and soil water soaking, natural vegetation. It should be emphasized that the soil database was used only for establishing the granulometric composition of soils and their watering, but the soil typological unit itself was not included in the assessment. The assessment of vegetation distribution was performed in order to analyse the areas where, due to the perennial vegetation cover, no real erosion occurs and where there is no possibility for it to occur in the long run. The intensity of erosive and deflation processes is strongly influenced by climatic factors. The coastal plain falls into one coastal area, throughout which the main perennial climate indicators vary little (Distribution of climatic regions 2014), therefore the influence of climatic factors on various parts of the Coastal Lowland has not been differentiated.

The current state of the relief was assessed using three criteria: its origin (genetic type), morphography of relief forms and morphometric indicators of relief forms. The database of the Lithuanian relief cadastre was used for this purpose.

The granulometry of sediments was assessed using the databases of soil, bogs and peatlands, and those of reclamation status and waterlogged soils. On the other hand, local climatic indicators, including the intensity of rainfall, are also very important when assessing surface erosion (López-Vicente, Guzmán 2021). The widely used USLE / RUSLE surface erosion models estimate the following indicators of surface morphometric parameters, local climate and economic activity: R = rainfall-runoff erosivity factor; K = soil erodibility factor; L = slope length factor; S = slope steepness factor, C = cover-management factor; P = support practice factor (Renard *et al*. 1991). The determination of the rainfall-runoff erosivity factor (R), which expresses the kinetic energy of a raindrop's impact and the rate of associated runoff is the most problematic. The R factor is a multi-annual average index that measures the kinetic energy and intensity of rainfall necessary to describe the effect of rainfall on sheet and rill erosion.

In Lithuania, assessment of the intensity of erosion processes based on local meteorological indicators is performed at the Kaltinėnai Research Station. The survey data characterize the western and central parts of the Žemaičiai Upland (Jarašiūnas *et al*. 2020). Until 2020, local meteorological observations in the Coastal Lowland were performed only episodically. For this reason, we applied a different method for the surface erosion potential assessment, which is based on the methodology used by A. Račinskas (Račinskas 1990). Stability of the surface erosion in cultivated fields is determined by several factors: the ratio of clay and sand particles in the surface sediment layer, slope inclination, humus content in soil, and the binary nature of soil structure (Motuzas *et al*. 1996; Račinskas 1990). The interaction between sediment granulometry and surface erosion is expressed by formula (1), and the interaction between humus and erosion by formula (2) (Račinskas 1990):

$$Z_g = 32.6 - 0.71\beta \quad (1)$$

$$Z_h = 44.68 - 35.7\ln\alpha \quad (2)$$

Where Z_g – is the amount of potential erosion due to sediment granulometry (m^3 / ha / year), Z_h – is the amount of potential erosion due to humus content (m^3 / ha / year), β – is the amount of clay particles (%), α is the amount of humus (%).

The amount of clay particles and humus content in soil were evaluated using the database of reclamation status and sodden soil, the database of soils, the LIDAR database of flood-prone areas and the database of crop fields.

Vegetation assessment was made using digital raster ortho-photo map, CORINE land cover and forest cadastre data databases. Based on them, the areas of forest, wetlands and bushes were identified.

The graphical database layer information was newly digitized using Adobe Illustrator software. In separate layers of the digitized information, the coordinates of the base points were determined, different land uses (cultivated fields, forests, urban areas) were distinguished and contours of boundaries were redrawn. Information layers were created using Adobe Illustrator software and were exported to dxf. files. Contour areas were calculated using the applet POINTandVERTEX, created by A. Bautrėnas, which automatically linked the position of base points with the map scale, calculated the contour area and linked it to the LKS-94 coordinate system.

RESULTS

Investigation into the intensity of erosion-accumulation processes in the Coastal Lowland was carried out in two phases. The influence of the morphometric relief fragmentation differentiation, as the most important factor in potential erosion, was assessed first of all.

Assessment of the potential intensity of geomorphological processes is based on the analysis of morphometric indices of vertical and horizontal surface dissection (Table 1).

Potential surface degradation is most influenced by the primary horizontal and vertical surface dissection (Table 2, Fig. 1). The most intensive surface destruction processes may occur on high steep slopes, less intensive on medium height medium inclination slopes, and less intense on low flat slopes. The performed analysis of the Coastal Lowland surface dissection shows that the most intensive surface destruction processes occur at the junction of the Coastal Lowland and Žemaičiai Upland, while the most intensive accumulation processes take place in the Nemunas Delta and marshy basins.

In the second phase, we identified the factors limiting potential erosion, which are related to the spread of humus content in soils, land use structure, forest distribution, spreading of urban areas, communication lines, soaked and drained lands, natural wetlands and wetlands. The following spatial databases and interactive maps were used when assessing these indicators: the dataset of reclamation status and sodden soils, the dataset of soils, the dataset of crop fields, the Lithuanian geomorphological map, LIDAR data of flood-prone areas, the dataset of forest cadastre and the digital raster ortho-photo map. The application of these data made it possible to estimate the extent of potential erosion much more accurately and to make

Table 1 Morphometric classification of relief forms (Česnulevičius 1998, 1999)

Relief forms			Height (depth) of forms		
			Low (to 10 m)	Medium (10–20 m)	High (over 20 m)
Hills (h)	Small	Slope length (m)	(h_1) 25–50	(h_2) 50–100	(h_3) over 100
		Slope inclination (°)	over 7	over 7	over 7
	Medium	Slope length (m)	(h_4) 50–100	(h_5) 100–200	(h_6) over 200
	size	Slope inclination (°)	3–7	3–7	3–7
	Large	Slope length (m)	(h_7) 100–200	(h_8) 200–400	(h_9) over 400
		Slope inclination (°)	1–3	1–3	1–3
Waves (w)	(w_{10}) Waves height up to 5 m, slope inclination – 3				
Plains (p)	(p_{11}) Surface inclination less than 0.5				

Table 2 Distribution of different morphometric relief types in the Coastal Lowland (km²).

Genetic relief types	Morphometric types of relief forms										
	h_1	h_2	h_3	h_4	h_5	h_6	h_7	h_8	h_9	w_{10}	p_{11}
Marginal moraine	3.4	1.2		28.4	702.3	7.8	9.2			105.9	31.7
Ground moraine	0.4						7.3			25.5	292.2
Glaciofluvial	1.1	0.7		0.8						0.6	17.0
Glaciolacustrine	9.4			2.1			3.1		3.3	157.8	484.0
Erosion				1.0□				0.7			
Aeolian	15.2	27.7		1.2	12.9					37.7	14.9
Fluvial	8.6	9.7	0.8	4.1						24.1	255.1
Littoral	0.2			1.5						30.8	148.3
Organiogenic										25.5	157.6

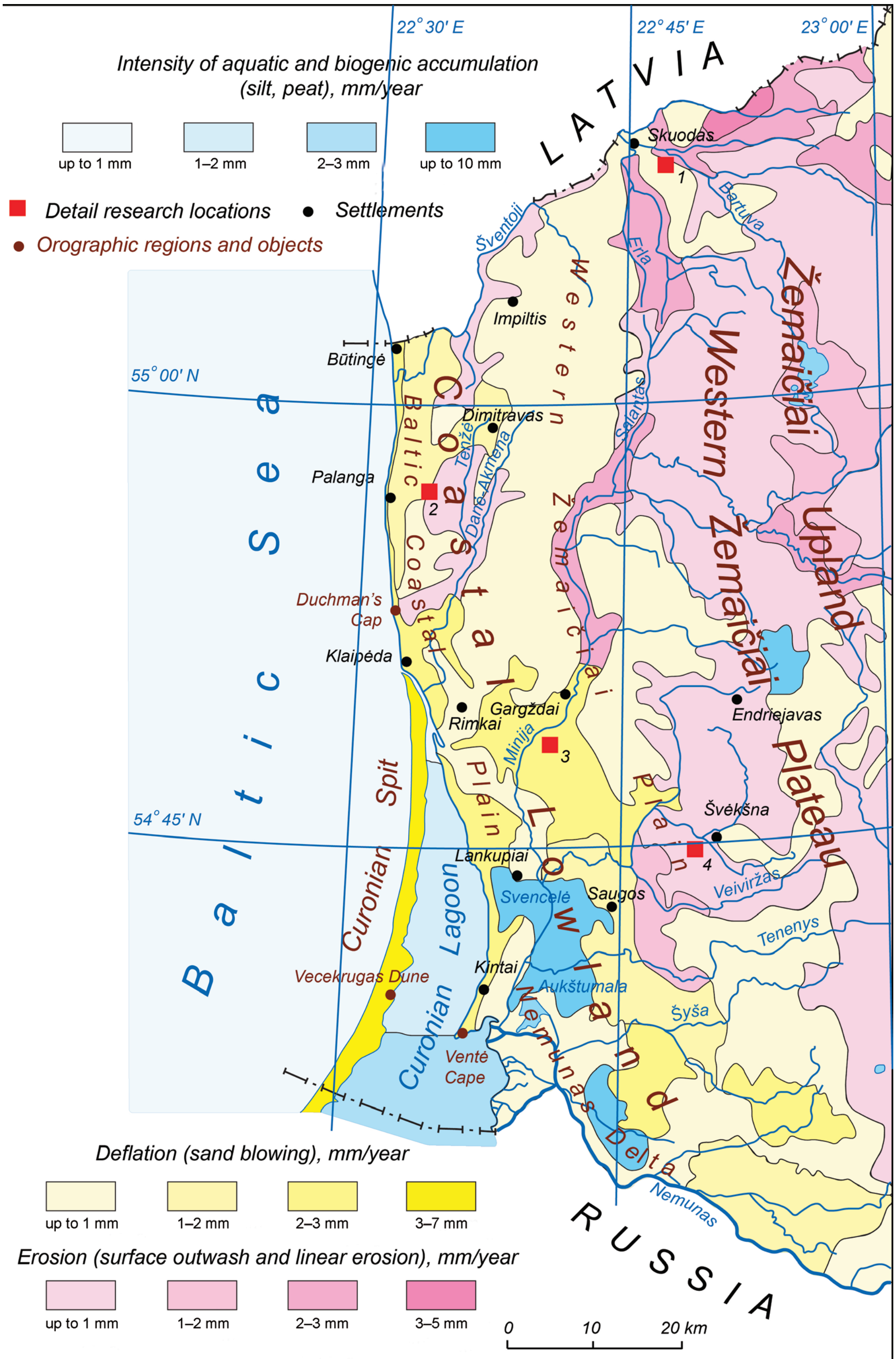

Fig. 1 Distribution of different intensity accumulation and erosion processes in Coastal Lowland. Study sites: 1 – Skuodas town environs, 2 – Vydmantai settlement environs, 3 – Gargždai town environs, 4 – Švėkšna settlement environs

it more similar to the intensity of actual surface erosion (Table 3).

The most intensive accumulation processes take place in a swampy relief depression, the largest areas of which are in the southern part of the Coastal Lowlands. The most intensive accumulation of organic sediments reaching up to 10 mm/year takes place therein. In the rest of the lowlands, the areas of organic accumulation are distributed fairly evenly. The size of wetlands varies from a few to several hundred hectares. The intensity of accumulation processes in these areas is much lower, i.e., it is in the range of 0.5–3 mm / year (Įvertinti šiuolaikinius upių ... 1990; Mikalauskas *et al*. 1986; Račinskas

1988; Račinskas, Morkūnaitė 1988; Česnulevičius *et al*. 1994; Vekeriotienė *et al*. 1991).

The spatial distribution of deflation processes is more diverse. In the northern and central parts of the Coastal Lowland, the sandy sediments blown to arable land amount to only 1 mm / year. In the southern (Nemunas Delta) and north-western (Palanga – Būtingė area) parts of the lowland, the process of deflation is more intense (1–2 mm / year), and in the central part it reaches 2–3 mm/year. The most intensive deflation processes take place in the Curonian Spit: in non-planted dune ridges, the average annual surface changes reach 3–7 mm, and after strong stormy winds, surface changes in separate parts of dunes are very large: 1.0–2.0 m (Įvertinti šiuolaikinius upių ... 1990; Česnulevičius *et al*. 2017; Morkūnaitė, Česnulevičius 2005; Račinskas 1988; Račinskas, Morkūnaitė 1988).

Table 3 Areas of the potential intensity of geodynamic processes taking into account the spatial distribution of their limiting factors

No.	Intensity of accumulation / erosion layers, mm	Area, km²	Percentage
1	Accumulation (to 1 mm)	10.4	0.33
2	Accumulation (1–2 mm)	223.5	7.14
3	Accumulation (2–3 mm)	172.5	5.50
4	Accumulation (3–10 mm)	168.6	5.38
5	Deflation (to 1 mm)	1214.8	38.80
6	Deflation (1–2 mm)	348.3	11.12
7	Deflation (2–3 mm)	431.8	13.79
8	Deflation (3–7 mm)	15.9	0.50
9	Erosion (to 1 mm)	367.1	11.72
10	Erosion (1 – 2 mm)	33.2	1.06
11	Erosion (2–3 mm)	140.9	4.50
12	Erosion (3–5 mm)	4.3	0.16

Intensity of the erosive processes taking place in the Coastal Lowland is uneven. In the southern part of the lowlands, their intensity reaches 1–2 mm / year. In the northern part (in the vicinity of the Danė-Akmena River valley) and near smaller rivers (the Veiviržas, Tenenis, Šyša), erosion is more intense (2–3 mm / year). It is most intense on the slopes of the

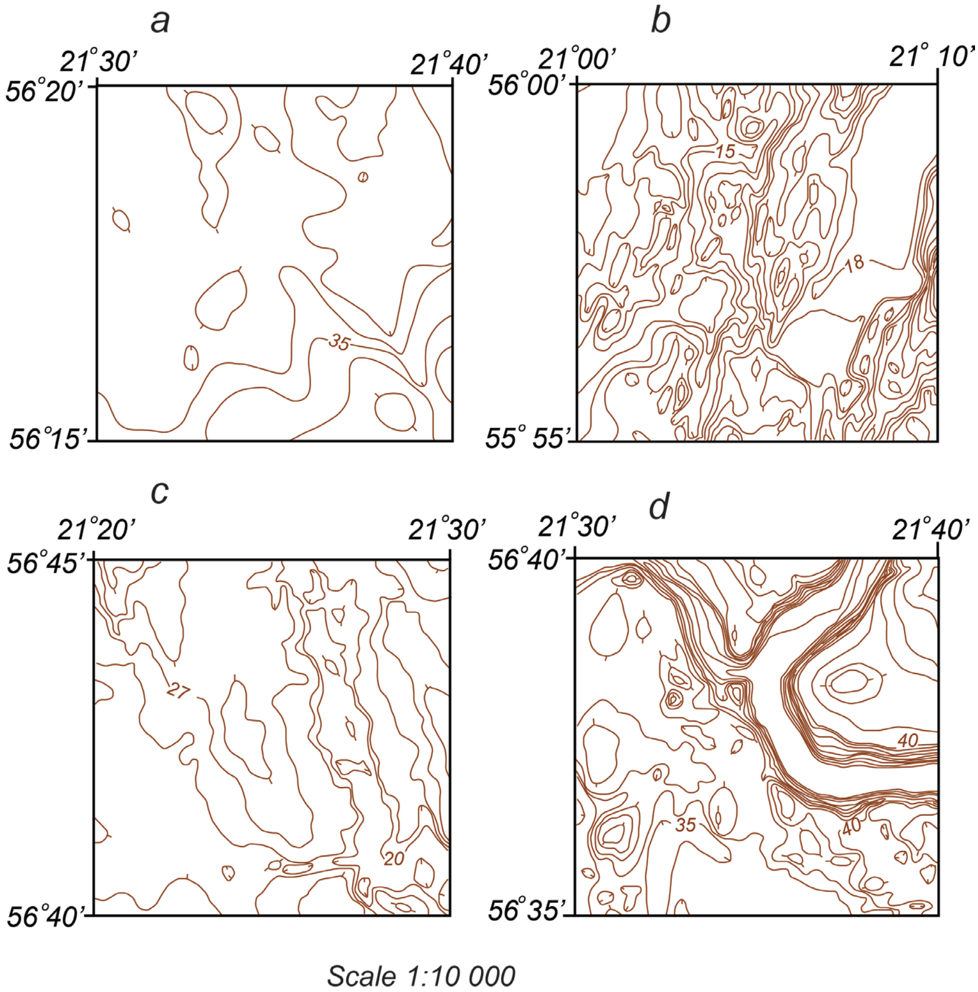

Fig. 2 Scattering of surface roughness: a – the Western Žemaičiai Plain (the N–W part of ground moraine, Skuodas town environs), b – the Baltic Coastal Plain (Vydmantai settlement environs), c – the Western Žemaičiai Plain (the S–W glaciolacustrine part, Gargždai town environs), d – the Western Žemaičiai Plain (the S–W part of ground moraine, Švėkšna settlement environs). Contour lines are drawn every 1 m

Minija River valley, where the annual surface runoff and dredging of linear erosive forms reaches up to 4 mm / year and more (Įvertinti šiuolaikinius upių ... 1990; Mikalauskas *et al*. 1986).

Scattering of surface roughness, morphometric relief types, and spatial intensity distribution of potential accumulation, deflation and erosion processes in different parts of the Coastal Lowland are presented in Figures 2, 3 and 4.

DISCUSSION

The intensity of temporary geodynamic processes depends mostly on the primary surface roughness, regional climatic conditions, local climatic phenomena and economic activities, which initiate natural geodynamic and purely anthropogenic surface-changing processes.

In the areas shaped during the last glaciation, the age of relief and epigenetic processes are highly important factors in reshaping the surface. The epigenetic processes that changed the terrain formed by the glacier in the early glacial period can be divided into two groups:

1. Epigenetic processes that created meso-rank relief forms. Such relief forms are mapped on large-scale maps. During cartometric measurements, it is possible to evaluate the morphometric indices of relief forms, and to apply mathematical models for predicting their further development, based on empirical field research data.

2. Epigenetic processes that created micro-rank relief forms. Relief forms of such a size are fixed only when performing very large-scale surface mapping, which significantly limits the possibility of applying distance-based methods, as very large-scale maps are created only for typical limited-size areas (key-areas). The data obtained in this way are highly desirable, but due to their episodic nature, the terrain development models are suitable only partially.

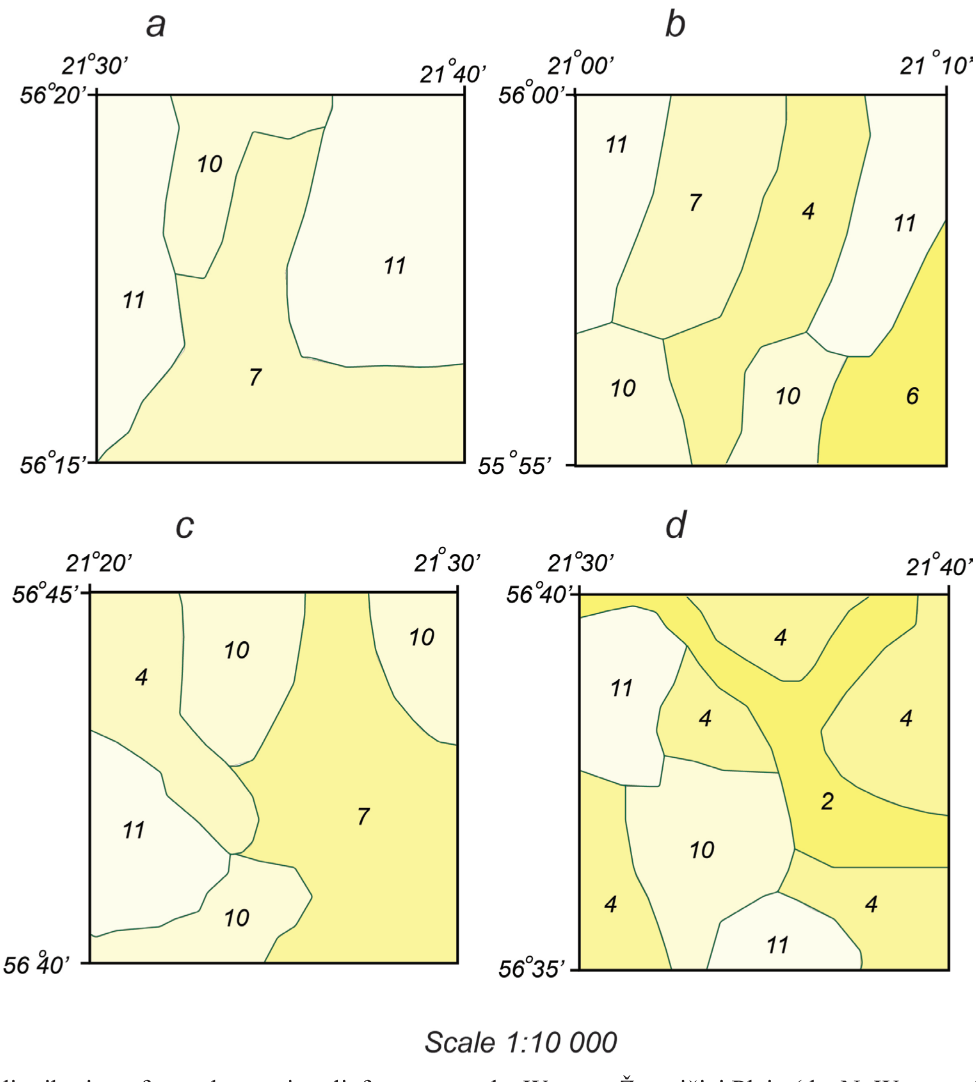

Fig. 3 Spatial distribution of morphometric relief types: a – the Western Žemaičiai Plain (the N–W ground moraine part, Skuodas town environs), b – the Baltic coastal plain (Vydmantai settlement environs), c – the Western Žemaičiai Plain (the S–W glaciolacustrine part, Gargždai town environs), d – the Western Žemaičiai plain (the S–W ground moraine part, Švėkšna settlement environs). Indexes of morphometric relief types are explained in Table 1

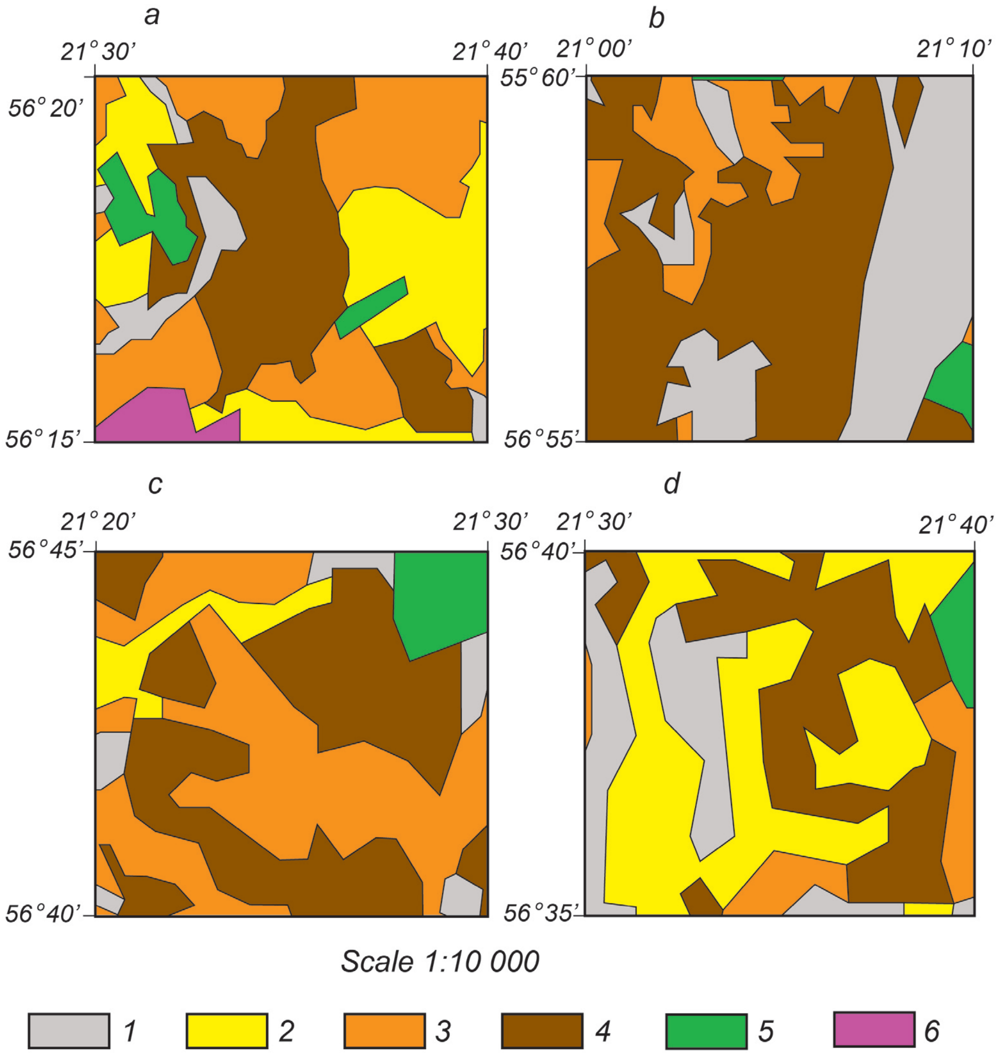

Fig. 4 Spatial distribution of erosion-accumulation processes in different areas of the Coastal Lowland by intensity a – the Western Žemaičiai Plain (the N–W ground moraine part, Skuodas town environs), b – the Baltic Coastal Plain (Vydmantai settlement environs), c – the Western Žemaičiai Plain (the S–W glaciolacustrine part, Gargždai town environs), d – the Western Žemaičiai Plain (the S–W ground moraine part, Švėkšna settlement environs/), 1 – biogenic accumulation (up to 2 mm / year), 2 – deflation (sand blowing) (up to 2 mm / year), 3 – erosion (surface outwash and linear erosion) (up to 2 mm / year), 4 – erosion (surface outwash and linear erosion) (2–3 mm / year), 5 – forests, 6 – urbanized areas

The indicators used in relief development models can be divided into two groups: variables and relatively stable indicators in time-space terms. Spatial land use data are among the most appropriate indicators in time-space terms. Aerial photography of the territory provides the most accurate and reliable data. However, such work is performed once every 10 years or even less frequently. This means that after a period of 5 years, the reliability of such data decreases significantly. The use of UAV for the revision of such data is possible only in small coverage areas, which reduces their reliability and limits their applicability in regional surveys.

One of the ways to obtain accurate spatial data is to use space photo-images. In that case, however, the researcher encounters the problem of having to establish the criteria for classifying land use for space images by himself. In this case, quite complex supervised classification methods are employed (Galinienė *et al*. 2019; Bagdanavičiūtė *et al*. 2018; Estima, Painho 2019; Hütt *et al*. 2016; Kafi *et al*. 2014). The use of supervised and unsupervised space-based methods for land cover mapping has shown that unsupervised (free) classification is not suitable for data acquisition and further use. The supervised classification provides more accurate interpretative data that can be used in further studies, e.g., for assessing the spatial distribution of land cover for the analysis of geodynamic processes (Galinienė *et al*. 2019).

It is becoming clear that it is most appropriate to use large-scale cartographic databases for the modelling of geodynamic processes. They guarantee the accuracy of spatial boundaries and the reliability of the quantitative indicators obtained.

CONCLUSIONS

The analysis of surface degradation and accumulation processes showed that the surface degradation potential is mainly determined by the primary horizontal and vertical relief roughness. In the Coastal Lowland, the most intensive surface erosion processes take place on steep slopes of deep river valleys. Less intensive erosion processes occur in flattened glacial edge formations, where medium-height and medium-steep hill slopes predominate. Erosion processes of the lowest intensity take place on the lower parts of flat slopes.

Another important factor determining surface erosion is the impregnation of soil cover. Soaked loam deposits, especially on the slopes of river valleys, become more fluid. As a result, linear micro-washouts are formed, which, under favourable conditions, can transform into deep washouts or potholes.

A prerequisite for deflation processes to take place is the temporarily or permanently exposed surface. Such conditions arise in the southern part of the Coastal Lowland in spring, where spring ploughing and rising winds cause non-intensive but constant sand blowing. The most favourable conditions for sand blowing are in the vegetation- uncovered dunes of the Curonian Spit and in the narrow stretch of beaches along the Baltic coast.

Epigenetic surface transformation (formation of shallow surface depressions, coastal embankments in the Nemunas Delta) created good conditions for biogenic accumulation in the southern part of the Coastal Lowland, where groundwater and high excess moisture are close to the surface.

The assessment of the Coastal Lowland relief performed based on the analysis of the terrain roughness and the above-mentioned databases shows that the most intensive surface erosion processes take place at the intersection of the Coastal Lowland and the Žemaičiai Upland, and the most intensive accumulation processes occur in the Nemunas Delta and swampy depressions.

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