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Morphometric indicators of insular and marginal morainic uplands (based on LiDAR data) of the Last and pre-Last Glaciations, case of Lithuania

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Abstract. The LiDAR-based digital elevation models of representative sample areas of morainic uplands of the Last (Weichselian) and pre-Last (Saalian) Glaciations in Lithuania were selected, and the terrain ruggedness index (TRI) and slope angles (SAs) were calculated. Former hypsometric studies of the topography in Lithuania were mainly dealing with the indication of maximum, minimum or average altitudes of relief derived from topographical maps. The SAs and TRI were calculated for the pattern areas (16 × 16 km) and their central smaller parts (5 × 5 km). In order to test how much morphometric parameters are dependent on the size of a sample area, smaller areas (located in the central parts of all five patterns) were analysed in a similar way, calculating SA and TRI values. The same order of the mean values of SAs was determined: the steepest slopes are characteristic of the Tauragnai, Plateliai and Vištytis patterns, and the gentlest slopes of the Varniai and Medininkai patterns. The steepest slopes and the highest TRI were determined for the marginal morainic uplands of the Last (Late Weichselian) Glaciation. The age of the insular Žemaičiai (Samogitian) Upland is under discussions so far. It was proposed by other researchers earlier that the core of the insular Žemaičiai Upland height formed during the Saalian Glaciation and this core is covered by a thin cover of Weichselian deposits. The morphometric parameters display that the highest maturity of the relief is characteristic of the southern slope of the insular Žemaičiai Upland and the Medininkai Upland of the Saalian age. This indicates a likely similar age of both uplands.

Keywords*: digital elevation models; terrain ruggedness index; slope angles; maturity of relief; Weichselian; Saalian*

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INTRODUCTION

The glacial morainic topography in marginal and insular uplands is very diverse, variable and complex. In areas of Quaternary glaciations, morainic formations are subject of geological and geomorphological mapping that aims to determine the genesis, composition and age of landforms. The maturity of landscape is one of the aspects of the age of relief and is reflected by morphometric parameters like slope angles and others. Former hypsometric studies of the topography of Lithuania were mainly dealing with analysis of maximum, minimum or average elevation of the relief (Paškauskas, Vekeriotienė 2013).

Former morphometric-morphographic maps of Lithuania were constructed on a regional scale and depicted a relative elevation of landforms, length and angle of their slopes and landform count per 1 km^2 as the main indices describing the relief (Lietuvos...2014). According to elevation, landforms were classified into low (up to 10 m), medium (10–20m) and high (over 20 m). According to slope length, they were classified into small (up to 200 m), medium (up to 400 m) and large (up to 600 m). According to slope angle, they were classified into flat (1–3°), moderately steep (3–7°) and steep (over 7–11°). Analysis of relative and absolute elevation of the relief of the Saalian age based on the relative hypsometric levels showed morphogenetical equilibrium and harmonious development of the relief (Paškauskas, Vekeriotienė 2013).

Historically, the morphometry of landforms was identified and mapped from topographical maps and more recently from digital elevation models (Pike *et al*. 2009; Lamsters, Zelčs 2015; Lamsters 2012). Over the past years, Light Detection and Ranging (LiDAR) laser scanning systems have been rapidly evolving to acquire ever-best accuracy and reliability (Kalantaitė 2015). Therefore, high-resolution digital elevation maps generated by airborne LiDAR are becoming very successful tools for geological mapping (Ojala, Sarala 2017; Webster *et al*. 2006; Johansson, Palmu 2013; Hartzell *et al*. 2014). For instance, the LiDAR-based mapping of the variable subglacial geomorphology in the central part of the Scandinavian Ice Sheet enabled to reveal ring-ridge type moraines and hummocks overlapping the drumlin ridges (Sarala *et al*. 2019). Another example – a new high-resolution terrain model of Latvia has revealed the presence of a large number of narrow linear landforms underlying the landforms of deglaciation time (Nartišs 2019).

Terrain ruggedness analysis is being applied in order to quantify topographic heterogeneity and thereby describe the character of landscape and divide it into units with comparable characteristics (Smith 2014). The difference of ruggedness is interpreted as reflecting the maturity of the landscape with the lowest ruggedness in the older landscape. For instance, this method was applied for identification of older landscapes west of the maximum extension of the Ristinge ices stream in Denmark (Jacobsen, Platen-Hallermund 2013).

The aims of this research are to construct high-resolution LiDAR-based digital elevation models of selected representative sample areas of morainic uplands of the Last (Weichselian) and pre-Last (Saalian) Glaciations, to calculate selected morphometric indicators of morainic topography, and to compare these indicators in regard of the age of morainic formations. Also, it was envisaged to compare the morphometric parameters of the marginal and insular morainic formations of the Last Glaciation.

MATERIALS AND METHODS

Morphology and geological context of selected sample areas

The relief of Lithuania is mainly of glacial origin of the Late Weichselian age, except a small south-eastern part of pre-Last Glaciation (Saalian age) (Fig. 1). The average thickness of Quaternary deposits in Lithuania is 130 m and varies from 10–30 m in the northern part of the country, that is the area of prevailing glacial erosion, up to 200–300 m in the marginal and insular glacial uplands and buried valleys or palaeoincisions (Fig. 1) (Guobytė, Satkūnas 2011). The top part of the relief of Lithuania is composed of the Upper Weichselian (Nemunas) sediments (75.86% of the area), Late-Glacial and Holocene sediments (20.35%) and Saalian age (Medininkai) deposits (2.25%) (Guobytė *et al.* 2001). The plains are underlain by basal till and glaciolacustrine sediments. The lowlands, which lie below 100 m a.s.l., occupy a considerable part of the land area, so that only 20% of Lithuania consists of hilly uplands. Almost all these uplands are concentrated in the east of the country, excluding the insular Žemaičiai (Samogitia) Upland and Western Kurzeme Upland (southern part only). The insular Žemaičiai Upland is one of insular-type glacial uplands in the East Baltic area and the only one located in Lithuania. The insular Žemaičiai Upland is by 80–130 m higher than surrounding lowlands. A prominent, south-west–north-east orientated belt of hills and ridges, up to 20–45 km wide in eastern Lithuania, is known as the Baltija marginal uplands. These hills reach the heights of 150–250 m a.s.l.

The Medininkai Upland in south-eastern Lithuania is the north-western extension of the Ashmyany Upland located in north-western Belarus. The Medininkai Upland, reaching 200–290 m above sea level, is the highest part of Lithuania. The Medininkai Upland is mainly composed of marginal ice-pushed moraines formed by an active glacier (Fig. 1). The morainic landforms have a clearly elongated shape, with orientation from northwest to southeast. It is a characteristic feature of tills, glaciolacustrine and glaciofluvial sediments to be strongly glaciotectonically disturbed, reflecting an active glacial push towards southeast. No lakes exist today in the Medininkai Upland, and this is a characteristic feature. The cover of Quaternary deposits (Fig. 1) in the Medininkai Upland is, on average, 200–250 meters thick. The Saalian age of the Medininkai Upland was determined using a number of criteria: geomorphological, paleogeographical (presence of periglacial phenomena, hydrological pattern), geochemical and biostratigraphical (occurrence of the Eemian Interglacial deposits in surrounding lowlands) (Satkūnas, Guobytė 2013).

The methodological concept of this study is based on the idea that the Late Weichselian glacial morainic relief is a comparatively young accumulative type formation which is at a very beginning of geomorphic (erosional) cycle of the evolution of landforms. It is noticed that steeper slopes are characteristic of a young and fresh morainic relief (Late Weichselian age), and the slopes in older Saalian topography are longer and more gentle due to periglacial and gravitational

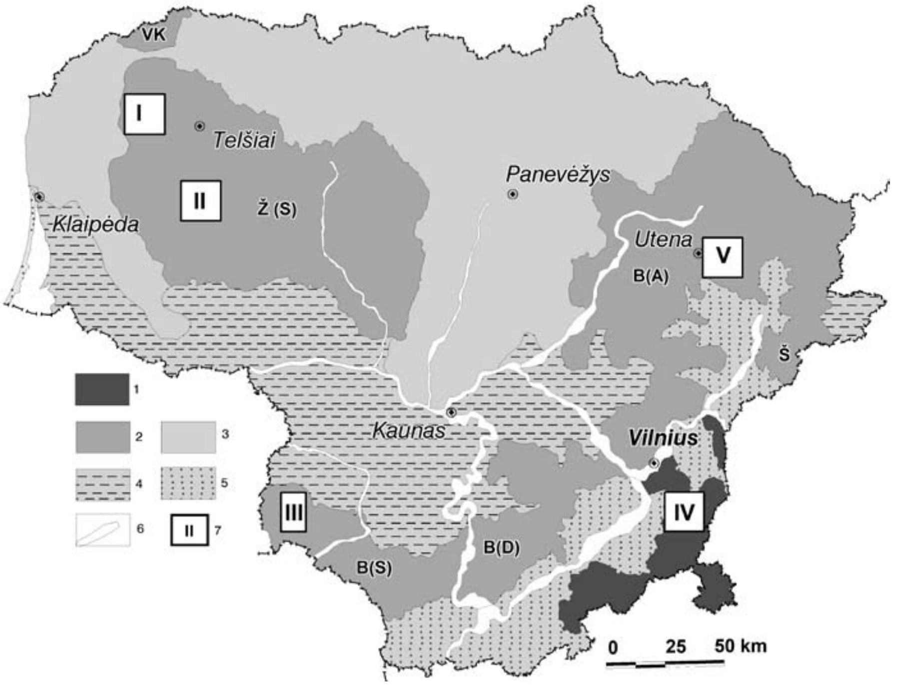

Fig. 1 Schematic geomorphological map of Lithuania: 1– relief of Saalian age: glacial Medininkai Upland; 2 – relief of Weichselian age: Ž(S) – insular Žemaičiai (Samogitija) Upland, VK – Western Kurzeme Upland, Š – Švenčionys Upland, B – Baltija marginal uplands, B(A) – Aukštaičiai Upland, B(D) – Dzūkai Upland, B(S) – Sūduva Upland; 3 – till plains; 4 –glaciolacustrine plains; 5 – glaciofluvial plains; 6 – valleys of major rivers; 7 – sample areas of morphometric analysis: I – Plateliai, II – Varniai, III – Vištytis, IV – Medininkai, V – Tauragnai (After Guobytė, Satkūnas 2011, modified)

processes, washing down material and accumulation of colluvium at the foots of slopes (Česnulevičius 1999). However, depending on geological composition, the maturing of erosional drainage network can even increase slope steepness and terrain ruggedness over time, e.g. forming a network of ravines like in badlands (Faulkner 2008). Such networks of erosion ravines are clearly visible on the slopes of the Medininkai Upland of the Saalian age.

For our morphological analysis, five sample areas (Figs 2–6) were selected from the geomorphological map at a scale 1:400 000 aiming that their morphogenetical (morphology and genesis of prevailing landforms) characteristics would be similar and comparable as much as possible. All of the sample areas are located in hilly and hummocky morainic uplands. The area from the Saalian relief was selected trying to identify an area less affected by the network of recent erosional ravines. It must be noted that there is no sample area which consists only of moraines. In all of them there are a number of landforms of glaciolacustrine and glaciofluvial origin as well as marshy areas, which have different morphological parameters compared with moraines and, in turn, affect terrain ruggedness values. For morphometric evaluation, the areas of lakes and the human-made formations (like roads and similar areas) were excluded.

The area of each sample area is 256 sq. km. Each sample area is of the shape of a square with dimensions of 16 × 16 km, except the Vištytis sample area, which is smaller (160 sq. km.) because of the lack of LiDAR data due to proximity of the state and EU border. To evaluate the influence of area of a sampling area, within each sample area a smaller (5 × 5 km) sample area was selected for evaluation with the same methods as the whole area. The sample areas I and II are located (Fig. 1) in the insular Žemaičiai Upland that is inside the territory of the Last Glaciation. The sample areas III and V are located in marginal morainic uplands of the Last Glaciation. The sample area No IV is outside the boundary of the Last Glaciation and is located in a morainic upland of the Saalian Glaciation.

Plateliai (No I). This sample area is located in the northern part of the insular Žemaičiai Upland. The relief is of glacial marginal and interglacial origin, with Lake Plateliai located in the central part. The variously hilly glacial marginal, glaciofluvial and glaciolacustrine relief is prevailing. The prominent kame massif is located in the southeast of Lake Plateliai. Large clay-covered flat-top hills are located in the northwest of the lake. Prevailing altitudes are 130–150 m a.s.l.

Varniai (No II). This sample area is located in the southern part of the insular Žemaičiai Upland. Prevailing surface altitudes are 160–180 m. a.s.l. The small hilly morainic topography is dominating, with hills 5–8 m high. In the central part, lakes Lūkstas and Paršežeris with marshy surroundings are located. High sandy kame type hills or massifs of these hills are com-

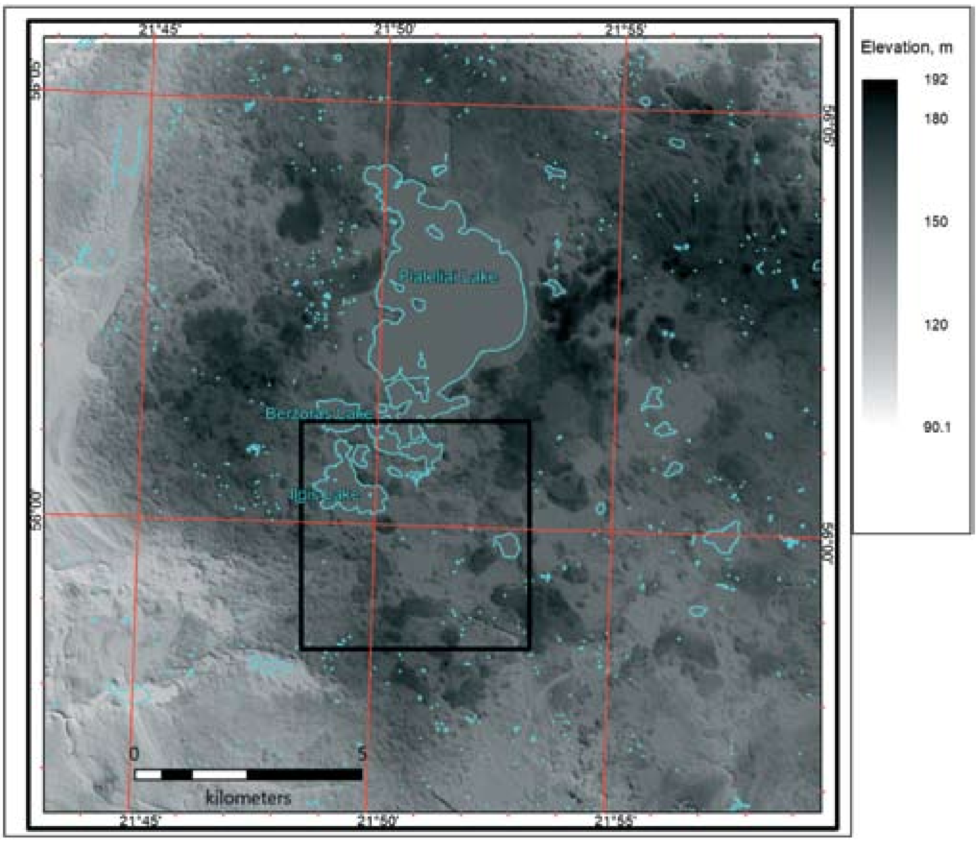

Fig. 2 The DEM of the Plateliai (No I) sample area (whole map). The black square in the most representative central part (I–1) is 5 × 5 km (25 sq. km)

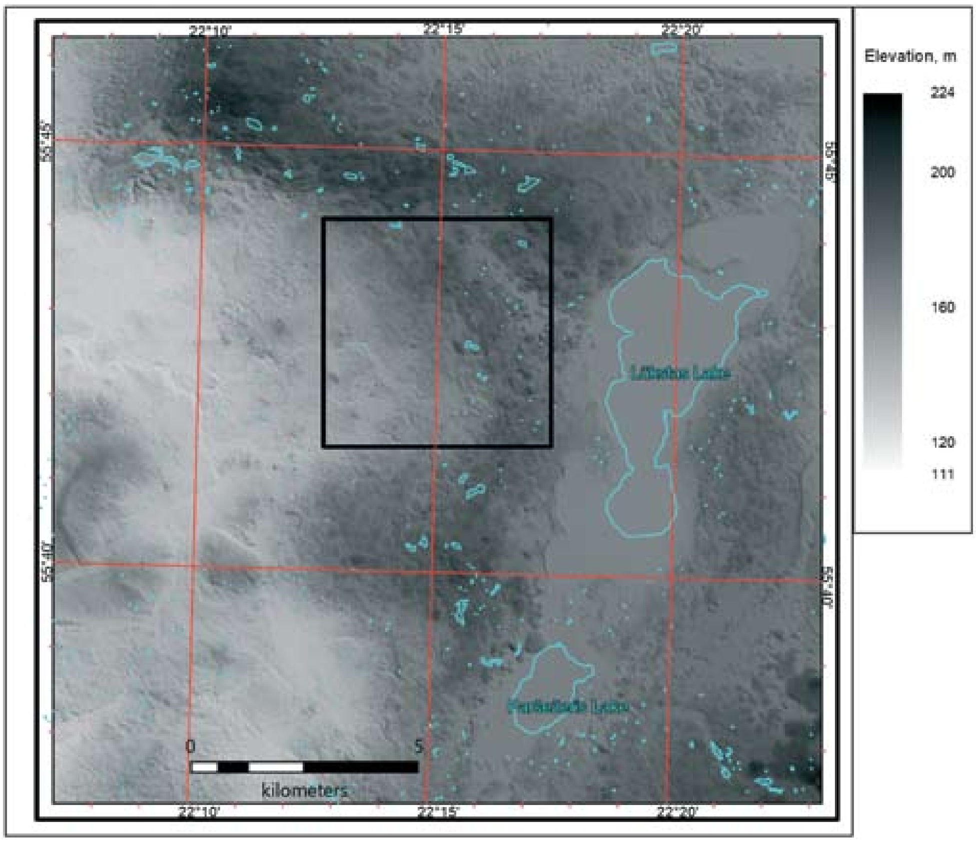

Fig. 3 The DEM of the Varniai (No II) sample area (256 sq. km, 16 × 16 km). The square in the most representative central part (II–1) is 5 × 5 km (25 sq. km)

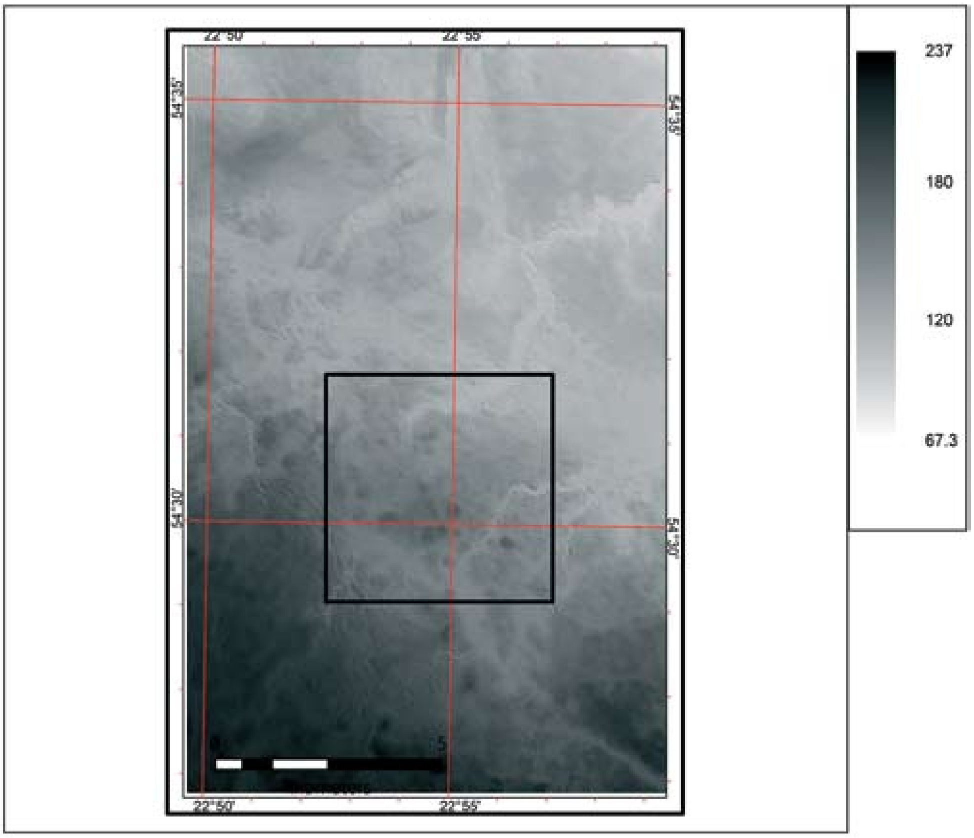

Fig. 4 The DEM of the Vištytis (No III) sample area (160 sq. km). The quadrangle in the most representative central part (III–1) is 5 × 5 km (25 sq. km)

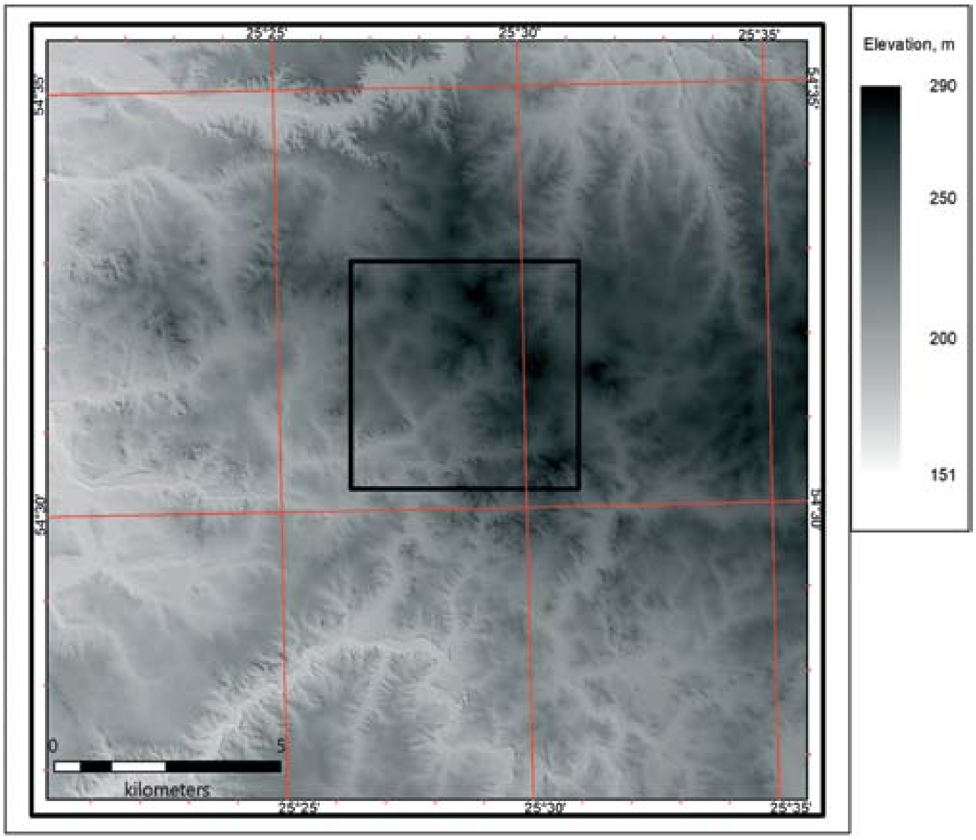

Fig. 5 The DEM of the Medininkai (No IV) sample area (256 sq. km, 16 × 16 km). The square in the most representative central part (IV–1) is 5 × 5 km (25 sq. km)

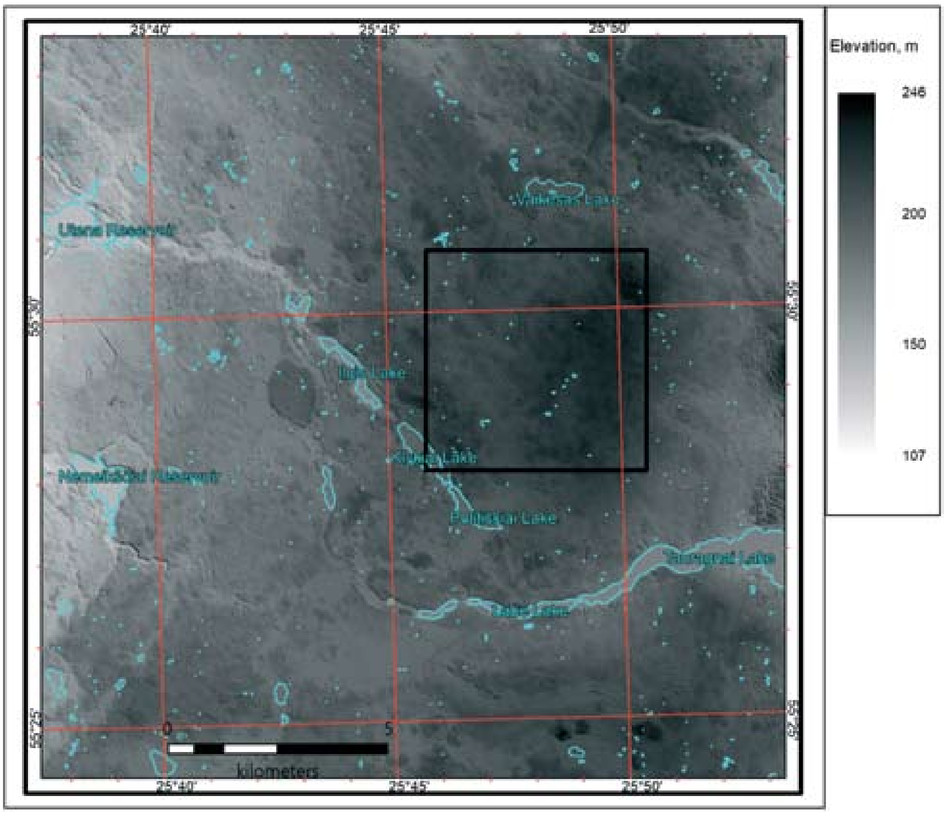

Fig. 6 The DEM of the Tauragnai (No V) sample area (256 sq. km, 16 × 16 km). The square in the most representative central part (V–1) is 5 × 5 km (25 sq. km)

mon for the area. Also, morainic, clay-covered high flat-top hills are present with altitudes of 180–190 m a.s.l.

Vištytis (No III). This pattern is located in the Sūduva Upland, the southern part of the Baltic marginal uplands. Topography is variously hilly with prevailing small and medium morainic hills. Some kame type high hills and massifs are located. The tunnel valley oriented from NW to SE dissects the area. The surface altitudes go lower from south to north – from 200 to 100 m a.s.l.

Medininkai (No IV). This sample area is located outside the boundary of the last Late Weichselian Glaciation in the Medininkai Upland of Saalian age. The glacial morainic relief is prevailing, only in a few hills the surface is composed of gravel and sand or sandy silty deposits. Prevailing altitudes or topography are 210–260 m a.s.l. Surface is wavy, undulating with single hills characterized by gentle long slopes and wide dry (boggy in some places) valleys between hills. The ravines of periglacial thermal erosion – the movement of land masses due to the thawing of permafrost are characteristic features.

Tauragnai (No V). The sample area is located in the Aukštaičiai Upland, the northeast part of the Baltija marginal uplands. Morainic topography with small and medium hills prevails; however, single high sandy hills or clay-covered flat-top hills are located there. Deep tunnel valleys (e.g. the Tauragnai, the deepest lake (depth up to 62.5 m) in Lithuania) oriented from NW to SE dissect the area. The prevailing altitude of topography is 180–200 m a.s.l.

Data analysis methods

Digital elevation models (DEMs) of each sample area were generated using LiDAR data which were obtained during the airborne missions carried out in 2009–2010 (source of information: National Land Service under the Ministry of Agriculture of Lithuania – SEŽP_0,5LT dataset). The average height of the LiDAR survey was 2.5 km. The average density of LiDAR measurements was 1–2 points per sq. m, and the accuracy was up to 0.1 m. DEMs were generated using the triangulation method. The cell size of each DEM was 1 × 1 m.

Slope angles (SAs) and terrain ruggedness index (TRI) parameters were chosen as the most representative indicators for the morphometric characterisation of relief. Slope angles reflect the steepness of slopes of elementary landforms (mesoforms), and the TRI reflects the density of mesoforms with different steepness. It is assumed that slopes of glacial landforms are getting less steep and a hilly/hummocky terrain is getting flatter due to hydroclimatic, gravitational and biological processes. As it was discussed above, the effect of the drainage network as a maturing factor is not significant in the young relief of the Late Weichselian age; however, this factor is present in the older relief of Saalian age. Nevertheless, the TRI and SAs are assumed as indicators of the comparative maturity of relief. In each sample area, SAs and TRI were calculated from DEMs using QGIS software (QGIS… 2020), and maps of distribution of these parameters were compiled. Lakes and artificial structures such as roads, channels, etc. were removed before calculation of SAs and TRI. Measurements of SAs and TRI were performed in two steps – firstly, for the whole sample area (I to V), and secondly, in their most representative central parts (smaller areas I–1, II–1, III–1, IV–1 and V–1, each covering 25 sq. km). This was done in order to compare morphometric indices obtained for bigger and smaller areas. For comparison of these sample areas, several indicators of descriptive statistics were calculated – minimal, maximal, mean and standard deviation values.

The topographic ruggedness index (TRI) was developed by Riley *et al.* (1999) to express the amount of elevation difference between adjacent cells of a DEM. It calculates the difference in elevation values from a centre cell and eight cells immediately surrounding it. Then it squares each of the eight elevation difference values to make them all positive and averages the squares. The TRI is then derived by taking the square root of this average. This parameter is calculated using formula $TRI = Y\left[\sum(x_{ij} - x_{00})^2\right]^{1/2}$, where x_{ij} is elevation of each neighbour cell to cell (0.0).

RESULTS AND DISCUSSION

The present morphometric study based on DEMs resulted in determination of statistical values of SAs and TRI of the relief of morainic uplands displayed in maps (Figs 7, 9) and raster diagrams (Figs 8, 10).

The raster histograms of frequencies of pixel values (Fig. 8) displayed that the highest frequency of gentle slopes is characteristic of the Medininkai sample area (No. V) of the Saalian age. Rather high frequencies of gentle slopes were determined for the sample areas I and II, both located in the insular Žemaičiai Upland. The highest frequency of steeper slopes is characteristic of the Baltija marginal uplands (sample areas III and V).

The lowest statistical mean values of slope angles (Table 1) are characteristic of the Varniai (4.00°) and Medininkai (4.06°) sample areas. The highest slope angle mean value was determined for the Tauragnai sample area (5.45°); however, rather high values were detected for the Plateliai and Vištytis sample areas (5.01° and 4.48°, respectively).

Table 1 Statistical values of slope angles (degrees) in sample areas

Area	Minimal	Maximal	Mean	Standard deviation
I Plateliai	0	81.922	5.009	4.100
II Varniai	0	75.316	4.026	3.112
III Vištytis	0	85.813	4.476	3.666
IV Medininkai	0	82.543	4.167	3.239
V Tauragnai	0	81.867	5.451	4.159

Table 2 Statistical values of TRI in sample areas

Area	Minimal	Maximal	Mean	Standard deviation
I Plateliai	0	13.262	0.239	0.180
II Varniai	0	8.526	0.200	0.135
III Vištytis	0	23.672	0.223	0.176
IV Medininkai	0	13.246	0.208	0.144
V Tauragnai	0	67.944	0.264	0.184

The highest frequency of low values and the lowest mean value of TRI (Table 2) was determined for the Plateliai sample area (No. I). The Tauragnai sample area (No. V) is the second according to the TRI mean value; however, the lowest frequency of low TRI values has to be admitted.

The highest TRI values were detected for the Tauragnai sample area (No V), and rather similar values are characteristic of the Vištytis and Plateliai sample areas.

Results of the present study indicate that the highest maturity of the relief is characteristic of the southern slope of the Žemaičiai Insular Upland and the Medininkai Upland (Saalian age) as reflected by TRI values.

In order to test how much morphometric parameters are dependent on the size of a sample area, smaller areas (located in central parts of all five sample areas) were analysed in a similar way, calculating SA and TRI values (Tables 3 and 4, Figs 10 and 11). The mean values of SAs in smaller sample areas reflect a pattern similar to that observed in larger areas: the steepest slopes are characteristic of the Tauragnai, Plateliai and Vištytis sample areas, and gentlest slopes of the Varniai and Medininkai sample areas. It is notable that the values of SAs in smaller areas are higher by 1.4 to 12.3% compared with the same values calculated from bigger areas. The same regularity was determined in the distribution of TRI values. The lowest TRI mean values are characteristic of the Varniai and Medininkai sample areas (II–1 and IV–1–), and the highest of the Tauragnai sample area. However, TRI values in smaller areas are higher compared with the same values of bigger areas, and the increase of TRI values is 0.9 to 11.7 % (except Varniai pattern, where decrease by 0.1 % was recorded).

Earlier morphometric studies have stated that the relief of Saalian age differs considerably from other ice marginal formations, and the hypsographic parameters show that the Saalian landforms have a mature surface (Paškauskas, Vekeriotienė 2013). According to the morphometric map of Lithuania

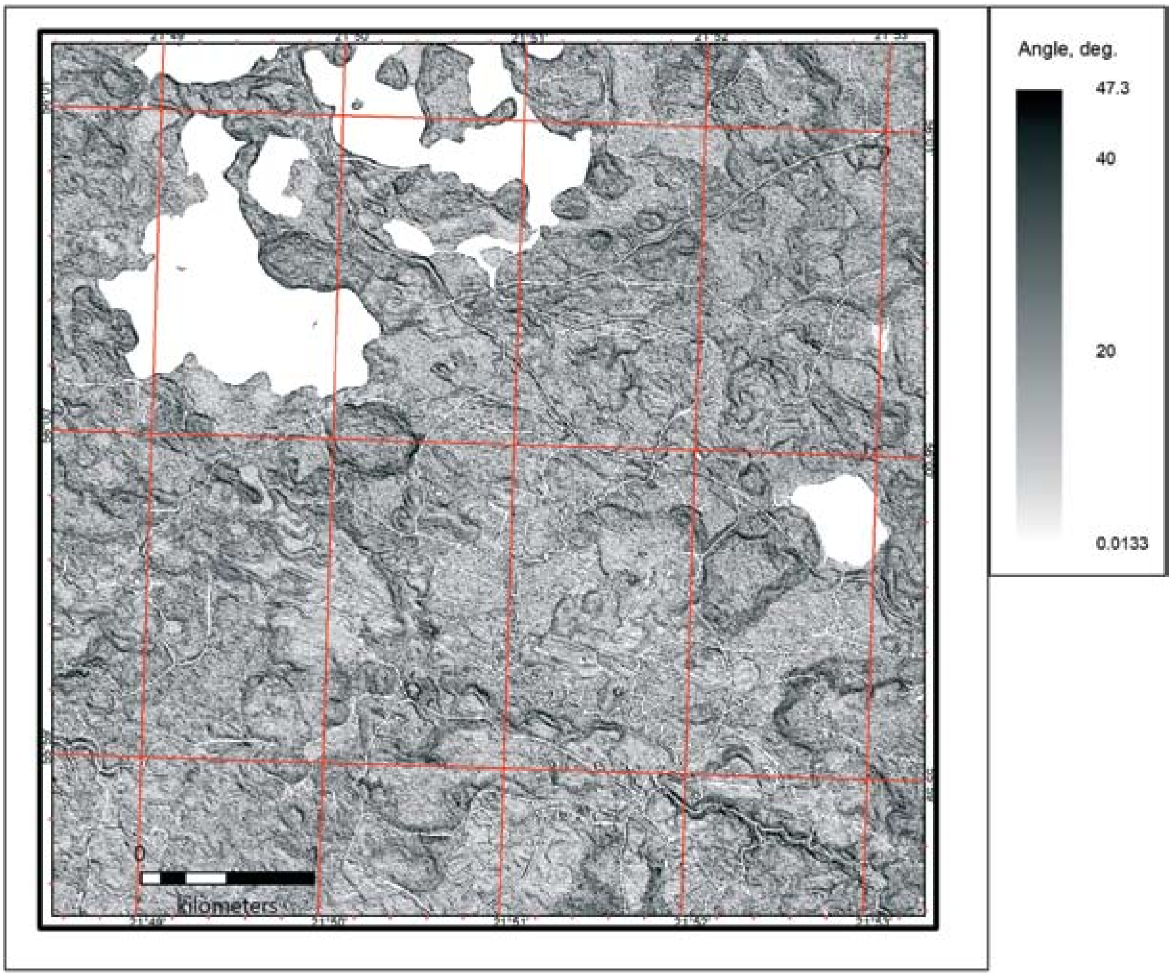

Fig. 7 Example of the map of slope angles. This fragment is located in the Plateliai sample area (No I)

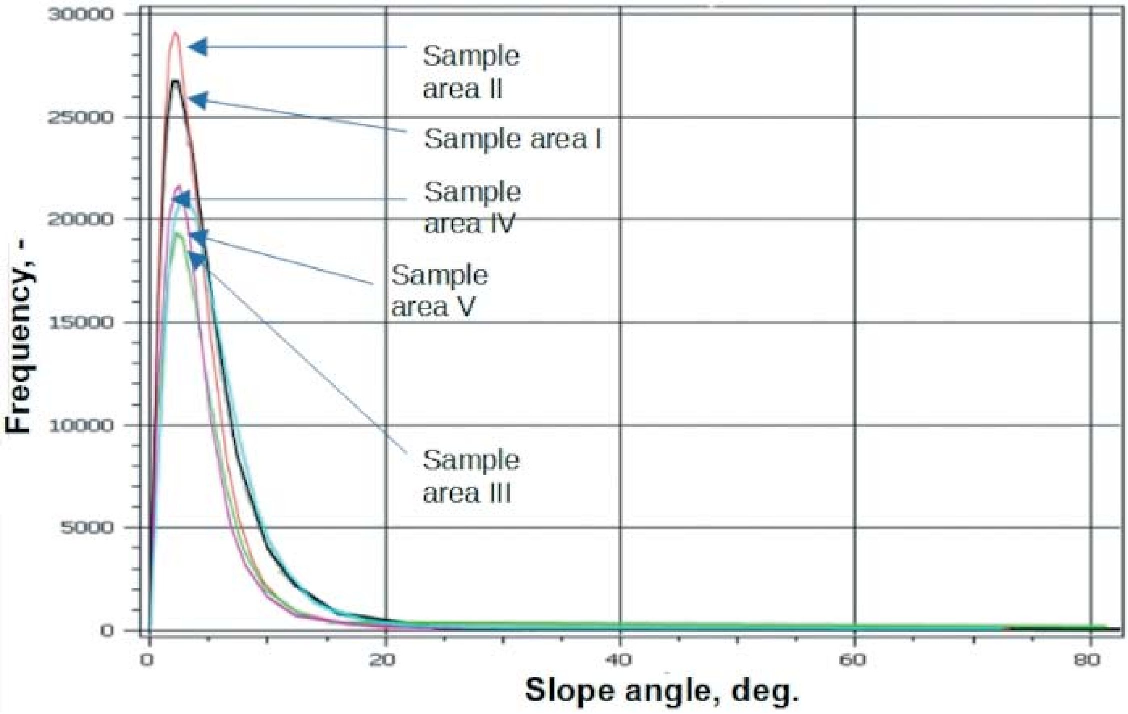

Fig. 8 Raster histograms of slope angle values of sample areas I to V

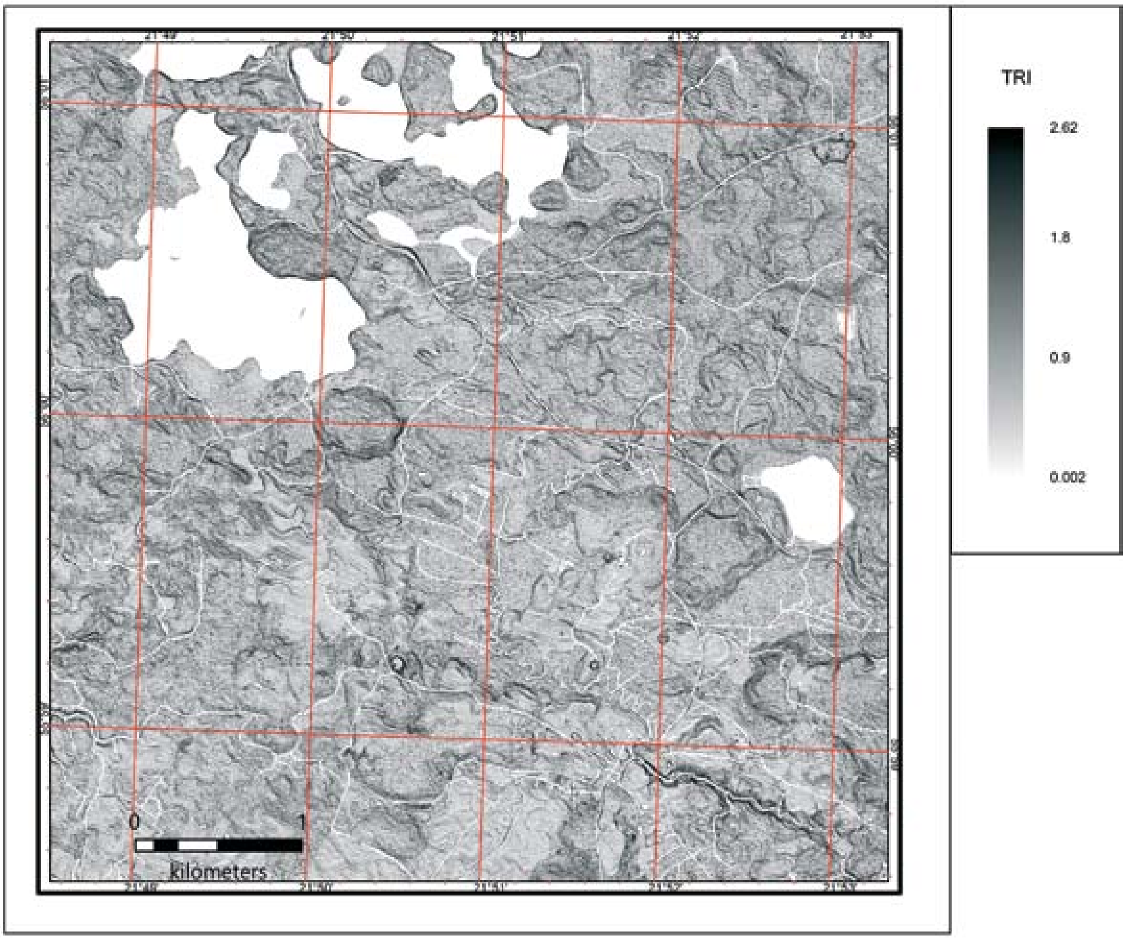

Fig. 9 Example of the terrain ruggedness index (TRI) map of the same area as in Fig. 7. This fragment is located in the Plateliai sample area (No I)

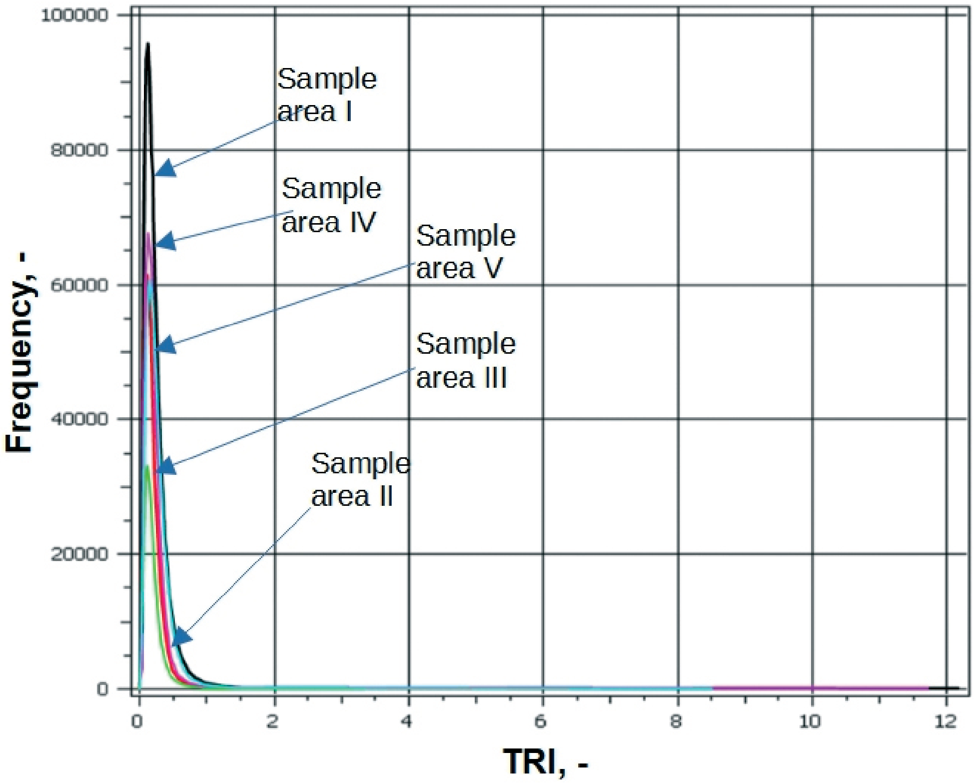

Fig. 10 Raster histograms of the TRI values of sample areas I to V

Table 3 Statistical values of slopes (smaller areas)

Area	Minimal	Maximal	Mean	Standard deviation
Plateliai I–1	0	63.921	5.628	4.470
Varniai II–1	0	63.639	4.083	3.084
Vištytis III–1	0	72.517	4.809	3.850
Medininkai IV–1	0	55.345	4.242	3.186
Tauragnai V–1	0	61.525	5.580	3.850

Table 4 Statistical values of TRI (smaller areas)

Area	Minimal	Maximal	Mean	Standard deviation
Plateliai I–1	0	5.447	0.267	0.196
Varniai II–1	0	4.567	0.200	0.132
Vištytis III–1	0	8.515	0.236	0.173
Medininkai IV–1	0	5.341	0.209	0.139
Tauragnai V–1	0	10.177	0.270	0.168

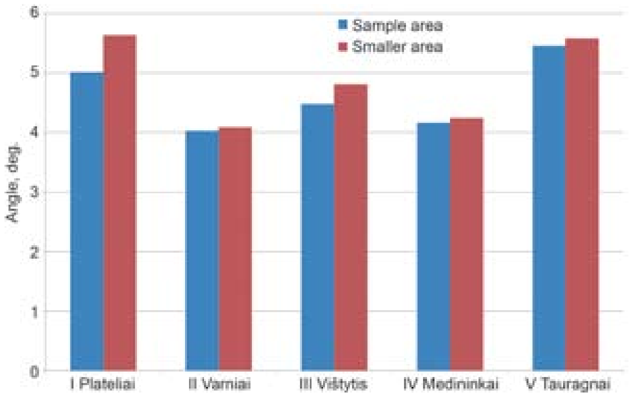

Fig. 11 Comparison of mean slope angle values in smaller and whole sample area

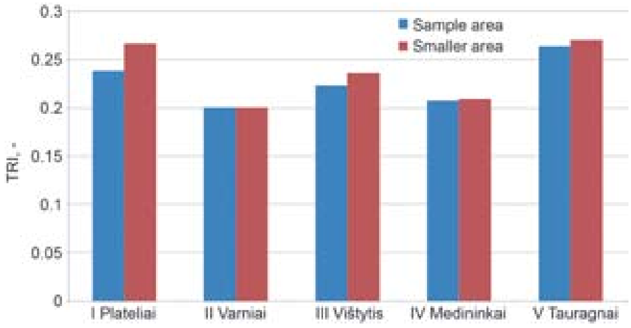

Fig. 12 Comparison of the mean TRI values in areas

(Lietuvos...2014), steep slopes are prevailing in the Medininkai and Švenčionys Uplands and less steep slopes are mapped in the Aukštaičiai and Žemaičiai Uplands. However, our morphometric analysis shows that the steepest slopes are characteristic of the sample areas of the Baltija uplands of the Last Glaciation. Less steep slopes were determined for the Medininkai and Varniai sample areas.

In the course of geological mapping at a scale 1:50 000 (Jusienė 2012) it was determined that the core of the Žemaičiai Insular Upland consists of sediments deposited during the Saalian Glaciation and this core is covered by a thin cover of Weichselian deposits. It is noteworthy that the morphometric parameters of the Varniai sample area are rather similar to the Medininkai sample area and therefore support the assumption of the Saalian age of the core of the Žemaičiai Upland. Nevertheless, the observed similarity is statistically weak and warrants further evaluation.

CONCLUSIONS

LiDAR data are very useful for the construction of detailed DEMs and determination of morphometric parameters. For the first time, slope angles (SAs) and the topographic ruggedness index (TRI) were determined for five morainic hilly and hummocky sample areas of Lithuania. Sample areas were identified from the geomorphological map of Lithuania (scale 1:400 000) aiming that their morphogenetical characteristics would be similar as much as possible. The calculated indicators reflect the homogeneity-heterogeneity of the surface; however, when used for areas with the relief of the same or similar genesis, the indicators imply the maturity of the relief based on the general assumption “smoother = older”. High slope values (higher than 40°) in all patterns occurred only in small areas. These values associated with small cell size (1 × 1 m) of the DEMs. So these values cannot be interpreted as general slope angles.

The SAs and TRI were calculated for the whole sample areas (16 × 16 km, except the Vištytis sample area) and their central smaller parts (5 × 5 km). A comparison of TRI and SA values indicates that higher values of both parameters are determined for smaller but most representative areas. Therefore, it is proposed that morphometric analysis could be effectively performed for areas of 5 × 5 km in order to compare the maturity of landscape. The steepest slopes are characteristic of the Tauragnai, Plateliai and Vištytis sample areas, and the gentlest slopes of the Varniai and Medininkai sample areas.

The highest TRI is characteristic of the Baltija marginal uplands (Tauragnai, Vištytis); however, this value is high also for the Plateliai sample area located in the insular Žemaičiai Upland. The lowest TRI values are typical of the relief in the Varniai and the Medininkai sample areas. The latter area is of Saalian age with the topography highly affected by periglacial processes. The morphometric parameters display that the highest maturity of the relief is typical of the southern slope of the insular Žemaičiai Upland and the Medininkai Upland. This indicates a likely similar age of both uplands.

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