DE GRUYTER OPEN Open Geosci. 2017; 9:509–524

Research Article

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Quantitative studies of the morphology of the south Poland using Relief Index (RI)

https://doi.org/10.1515/geo-2017-0039
Received Dec 08, 2016; accepted Sep 28, 2017

Abstract: The aim of this study was to introduce a new morphometric index named Relief Index (RI). RI is the ratio of the total length of the contour lines and the surface area at which they occur. This easily calculated index provides an objective quantitative measure of relief variability as an important feature in geomorphological studies. To achieve this goal, a highly detailed morphometric analysis was carried out using a high-resolution (1m×1m) DEM. Twenty one sample areas in southern Poland were examined. These analyses showed RI, as a good tool for rapidly evaluating topography heterogeneity in division into relief classes. I distinguished 4 classes of the Relief Index that classify earth surface considering the variability of the relief. Results of the calculations demonstrated that there is a significant correlation between RI and the local relief and slopes, but there is no correlation between RI and planar curvatures and TWI. The relief of the sample areas were analysed using geomorphometric parameters (slopes, local relief, planar curvatures). Moreover the influence of the DEM resolution on Relief Index values was examined.

Keywords: Relief Index, geomorphometry, DEM, LiDAR, south Poland, ArcGIS

1 Introduction

Relief of the land surface as an infinite set of irregular shapes has commonly been characterized in a descriptive way. Descriptive, that is qualitative characteristics of the relief is inexact, usually relative and subjective (some researchers describe terrain in terms such as undulating, broken, rugged, or dissected, *e.g.* Riley *et al.* [1]). Much better is quantitative method of research, which is accurate, objective and comparable. Nowadays the development of the digital methods and tools in earth sciences, especially geomorphometry, make this approach possible. Geomorphometry as the science which treats the geometry of the landscape attempts to describe quantitatively the landforms [2, 3]. Evans [4] distinguished specific geomorphometry (which measures the geometry of specific types of landforms) and general geomorphometry (the measurement and analysis of those characteristics of landforms which are applicable to any continuous rough surface). The digital elevation data are necessary to conduct quantitative topography studies. Presently, common availability of high-quality LiDAR data with high vertical and horizontal resolution make, that very precise geomorphometric calculations of the surface relief (or microrelief) became possible.

Quantitative analysis of topography on the base of DEMs resulted in the creation and development of many various topographic indexes and classification systems. Pike and Wilson [5] described elevation-relief ratio (E) of Wood and Snell [6] as one of six descriptive terrain parameters, which expresses the relative proportion of upland to lowland within a sample region. Mark [7] noted, that all measures of landforms can be considered to be in some way representative of the roughness of the surface. Usually, surface roughness remains as the most common generic term. There was a variety of terminology has been applied to study the roughness, including ruggedness [8], microtopography [9] or rugosity [10]. In a general sense, roughness refers to the irregularity or variability of a topographic surface. One of the widely recognized method for quantifying ruggedness was the Land Surface Ruggedness Index (LSRI) proposed by Beasom *et al.* [8]. This index was based on the assumption that ruggedness is a function of total length of topographic contour lines in a given area. Next Nellemann and Fry [11] and Riley *et al.* [1] worked on Terrain Ruggedness Index (TRI), which quantifies the total elevation change across a given area. Based on a Hobson method [12] developed for measuring surface roughness in geomorphology Sappington *et al.* [13] created a Vector Ruggedness Measure (VRM) to be used in a GIS that incorporates the heterogeneity of both slope and aspect. Other methods were proposed by Jenness [10], who

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quantifies ruggedness as the ratio of 3-dimensional surface area to planar surface area, or Grohmann *et al.* [14] - surface roughness as an expression of the variability of a topographic surface at a given scale, where the scale of analysis is determined by the size of the landforms or geomorphic features of interest. Another interesting indicator was Topographic Wetness Index (TWI) by Beven and Kirkby [15] which combines local upslope contributing area and slope, is commonly used to quantify topographic control on hydrological processes [16–19]. Jenson and Domingue [20] proposed tools for digital elevation modeling contain various options for the analysis of topographical attributes, such as algorithms for extracting drainage networks. Pike [21] introduced the concept of a geometric signature, a multi-variate description of topography using a suite of measures, and later [22] expanded the concept with a listing of 49 variables that could be grouped into 22 attributes. McNab [23] proposed a quantitative expression of the geometric shape of the land surface as Terrain Shape Index (TSI) or the Landform Index (LI) as the mean of eight slope gradients from plot center to skyline [24]. Buccolini and Coco described the role of the hillside in determining the morphometric characteristics of badlands [25] and developed Morphometric Slope Index (MSI) [26].

There have also been many concepts for terrain analyzing as tools for landform classifications. Weiss [27] presented an interesting concept of Topographic Position Index (TPI) which is the classification system and is simply the difference between the cell elevation value and the average elevation of adjacent cells. Guth in a series of papers [28–30] discussed an eigenvector technique to quantify terrain organisation (degree to which ridges and valleys align, and determines the preferred orientation). Hengl *et al.* [31] proposed an algorithm for automatic classification of main landforms, which consists of slope, plan curvature and shape complexity index. Jasiewicz and Stepinski [32, 33] presented novel geomorphons method for classification and mapping of landforms based on the idea that the earth surface can be described by the two complementary measures: relief-independent, local spatial pattern and the magnitude of the relief itself. To sum up one can conclude that issues of morphometric studies in geomorphology are still important and present (see more [34–39]).

The aim of this study was to develop an idea of Relief Index (RI) which I proposed on the Geomorphometry.org conference in Poznań [40]. This easily calculated index provides an objective quantitative measure of relief variability as an important feature in geomorphological studies. To achieve this goal, a highly detailed morphometric analysis was carried out using a high-resolution (1m × 1m) DEM. Twenty one sample areas in southern Poland (mostly upland and mountainous) were examined. The relief of the sample areas were analysed using geomorphometric parameters (slopes, local relief, planar curvatures). Moreover the influence of the DEM resolution on Relief Index values was examined.

2 Study areas

The research presented is related to relief analysis and therefore they were conducted in different geomorphological regions of the south and the middle Poland. Generally, the study areas are located in different morphogenetic zones, which are arranged in latitudinal strips. After the analysis of the hypsometric maps and DEM of Poland [41] I decided to choose areas with the characteristic morphology in accordance with relief types. Every relief type was represented by few locations. Each study site was carefully choosen to reflect the relief of the typical landscape (mountains, uplands, etc.). Interest has covered 21 areas (Figure 1) located in mountains (6 sites), intermountain basins (4 sites), uplands (6 sites) and lowlands (5 sites). Hypsometry of every study area is shown in the Figures 2 to 5. Every study site occupied an area of ca. 47 km^2 (each stite constists of 16 sections in subdivision of topomaps 1:5,000).

These study areas have different relief both in terms of origin and hypso- and morphometry. Mountain areas (sites 1-3) belong to the Caledonian-Hercynian zone, with crystalline massifs and old mountains folded type. There are characteristic aligned ridges, separated by large intermountain depressions [42]. Other places (sites 4-6) belong to the Alpine zone. The Tatras (4) are the highest mountain range situated in the Carpathians with a sharp ridgeline and a typical alpine character built of resistant granodiorites [43]. Sites 5-6 are built of Carpathian flysch and they create a typical grille arrangement of ridges and the mesh network of valleys. Areas lying in the mountains were characterized by high-relief (height SD 68-246 m), with high local relief values (518-1537 m) and lying at average altitude of 440-1700 m a.s.l. (Table 1).

Sites 7-10 belong to Sandomierz Basin and they are erosional depressions which were dissected by the river (denudation plains and terraces) [44]. These areas are characterized by low-relief (height SD 5-13 m), with local relief values 37-70 m and lying at average altitude of 163-228 m a.s.l. (Table 1).

Table 1: Basic height statistics

Study areas*	Heights [m a.s.l.]					
	min	max	range	mean	median	SD
Mountains						
1	587.6	1603.2	1015.6	1108.5	1127.1	225.9
2	326.0	844.4	518.4	452.1	441.1	67.9
3	498.5	1423.5	925.0	921.1	905.3	177.3
4	1021.0	2558.4	1537.4	1691.1	1693.2	245.7
5	584.8	1296.8	712.0	867.1	851.2	135.7
6	615.7	1345.7	730.0	963.0	946.4	136.4
Intermountain basins						
7	186.0	238.3	52.3	199.8	197.5	7.6
8	190.2	260.2	70.0	228.0	227.7	13.4
9	179.9	217.2	37.3	193.7	163.4	5.0
10	149.5	197.1	47.6	164.9	192.8	10.8
Uplands						
11	248.8	403.7	154.9	303.7	297.4	30.1
12	340.9	515.0	174.1	407.0	407.6	24.3
13	283.1	366.7	83.6	320.2	319.4	16.0
14	168.4	266.7	98.3	223.4	223.8	15.0
15	212.4	322.8	110.4	247.7	248.2	12.6
16	272.9	408.2	135.3	335.3	336.4	23.7
Lowlands						
17	172.0	249.5	77.5	186.3	182.3	11.5
18	149.2	208.2	59.0	175.3	171.9	10.5
19	127.4	168.0	40.6	144.4	144.2	7.8
20	128.1	171.1	43.0	142.1	142.5	6.0
21	136.3	188.8	52.5	157.2	154.9	10.5

* Area numbering is the same as in Figure 1

The other places (11-16) are located in a strip of uplands. Sites 11-14 belong to Silesian-Cracow Upland, which is the Palaeozoic-Mesozoic monocline with rocks of varying resistance that form the characteristic structural relief [43]. Areas 15-16 belong to the Malopolska Upland: site 15 consists of hills built of Cretaceous sandstones and Jurassic limestones, while the site 16 is built of lower Cretaceous sandstones [45]. Uplands are characterized by medium-relief (height SD 13-30 m), with local relief values 84-174 m and lying at average altitude 223-407 m a.s.l. (Table 1).

The last five places (sites 17-21) are situated in a strip of lowlands of the middle Poland of old-glacial origin. Site 17 belongs to Racibórz Basin – Tertiary Carpathian foredeep, which are the denudation plains and river terraces. Areas 18-21 are rather flat, double-glaciated landscape that consist mainly of denudation river plains and plains with fluvioglacial sediments [43]. Lowlands, similarly as intermountain basins, were characterized by low-relief (height SD 6-11 m), with local relief values 40-77 m and lying at average altitude 142-186 m a.s.l. (Table 1).

3 Data and methods

The primary research material were ESRI [46] ASCII Grid files (asc). All asc files were derived from LiDAR data cloud. Every asc file has 1m × 1m horizontal resolution, vertical accuracy ≤ 0.2 m [47] and occupies area of 5.3 km^2 (2.3 km × 2.3 km). This format consists of header information containing a set of parameters, which can be used to geocode the data. Although the header includes the coordinates of the lower left corner of the area covered by the grid the elevation data are given as strings of elevations, in row by row, starting from the upper left point on the grid [48]. Every study area consisted of 16 asc files. The shapes of study

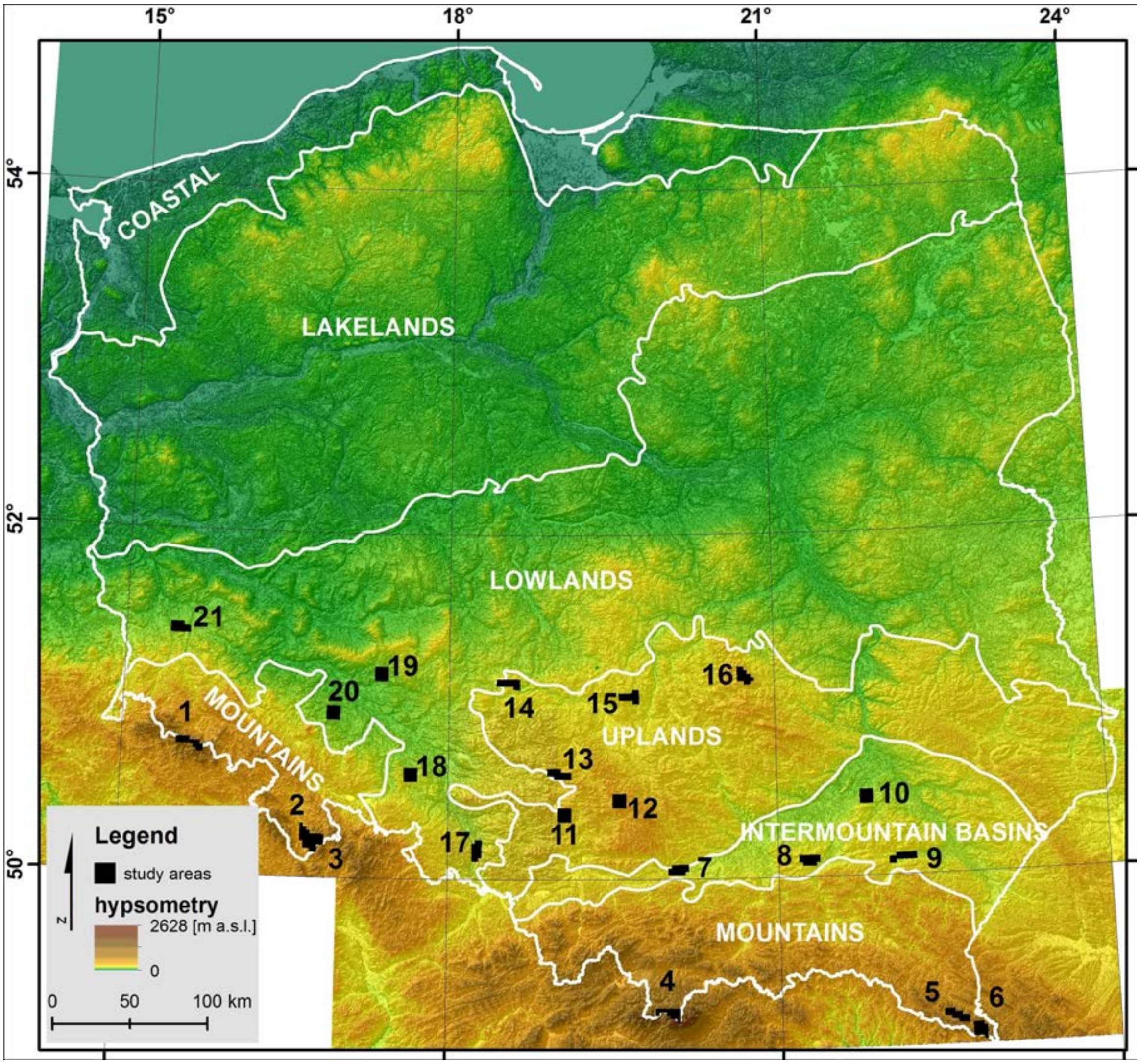

Figure 1: Study area locations: moutains (1 - Sudetes Mountains (Karkonosze), 2 - Sudetes Mountains (Kłodzka Basin), 3 - Sudetes Mountains (Śnieżnik Massif), 4 - Tatra Mountains, 5 - Bieszczady Mountains (Połoniny), 6 Bieszczady Mountains (Mt Tarnica); intermountain basins (7 - Cracow Gate, 8 - Tarnów Plateau, 9 - Podkarpacka Pradolina, 10 - Tarnobrzeg Plain), uplands (11 - Silesian Upland, 12 - Cracow-Częstochowa Upland, 13 - Woźniki-Wieluń Upland (Woźniki Threshold), 14 - Woźniki-Wieluń Upland (Wieluń Upland), 15 - Małopolska Upland (Radomszczańskie Hills), 16 - Małopolska Upland (Gielniowski Ridge); lowlands (17 - Silesian Lowland (Racibórz Basin), 18 - Silesian Lowland (Niemodlin Plain), 19 - Silesian Lowland (Oleśnica Plain), 20 - Silesian Lowland (Wrocław Plain), 21 - Silesian-Łużyce Lowland (Dolnośląskie Forest)

areas are irregular, due to the different arrangement of the characteristic relief elements (see Figure 2-5).

The distribution of the height data (in DEMs) did not always have a normal character (Figure 6). The distribution asymmetry usually was right-skewed, which means that most of the amount is below the average. For this reason I decided to post median as the optimal value that characterizes the average altitude of the area. The most similar to a normal distribution histograms were find for the mountains (sites 3-6).

The quantitative studies of the morphology of the south Poland were carried out by using Relief Index (RI). Relief Index is a simple mathematical tool for a rapid assessment of the relief variability. It is also an objective quantitative measure of the relief amount, diversity of topography. This RI index is based on the ratio of the summary length of the contour lines and the planar surface area at which they occur:

$$\mathrm{RI} = C_L/A_P \ [\mathrm{m/m^2}]$$

where: C_L is total length of contour lines, and A_P is planar surface area.

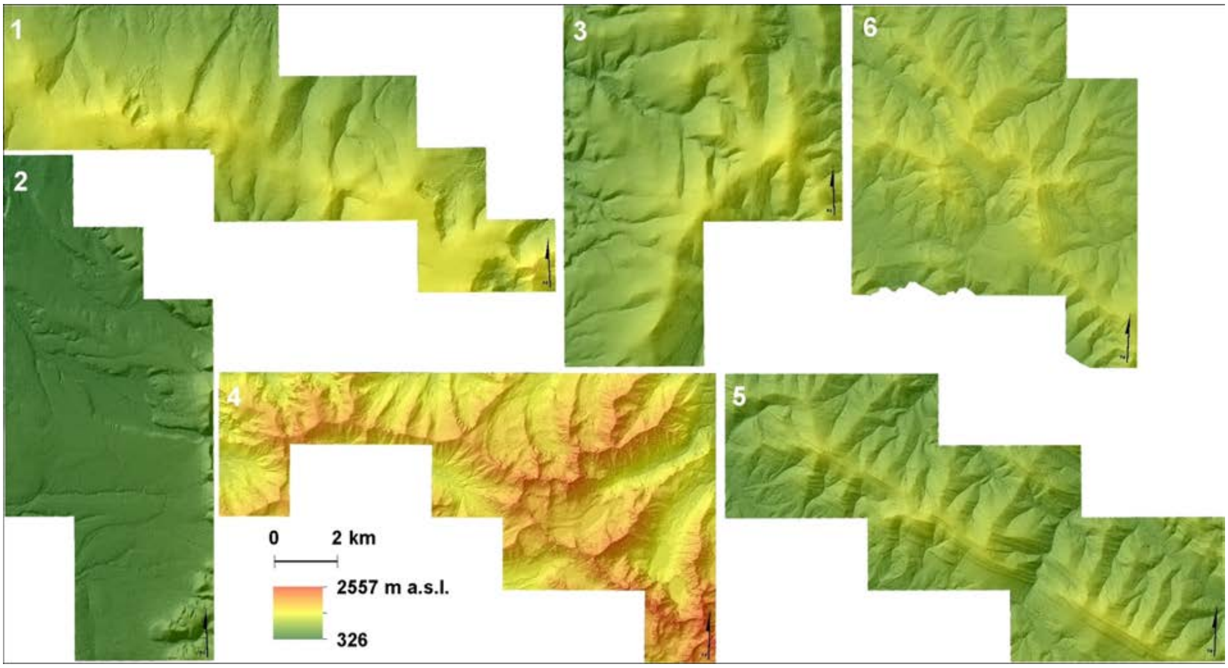

Figure 2: Hypsometry of study areas - mountains

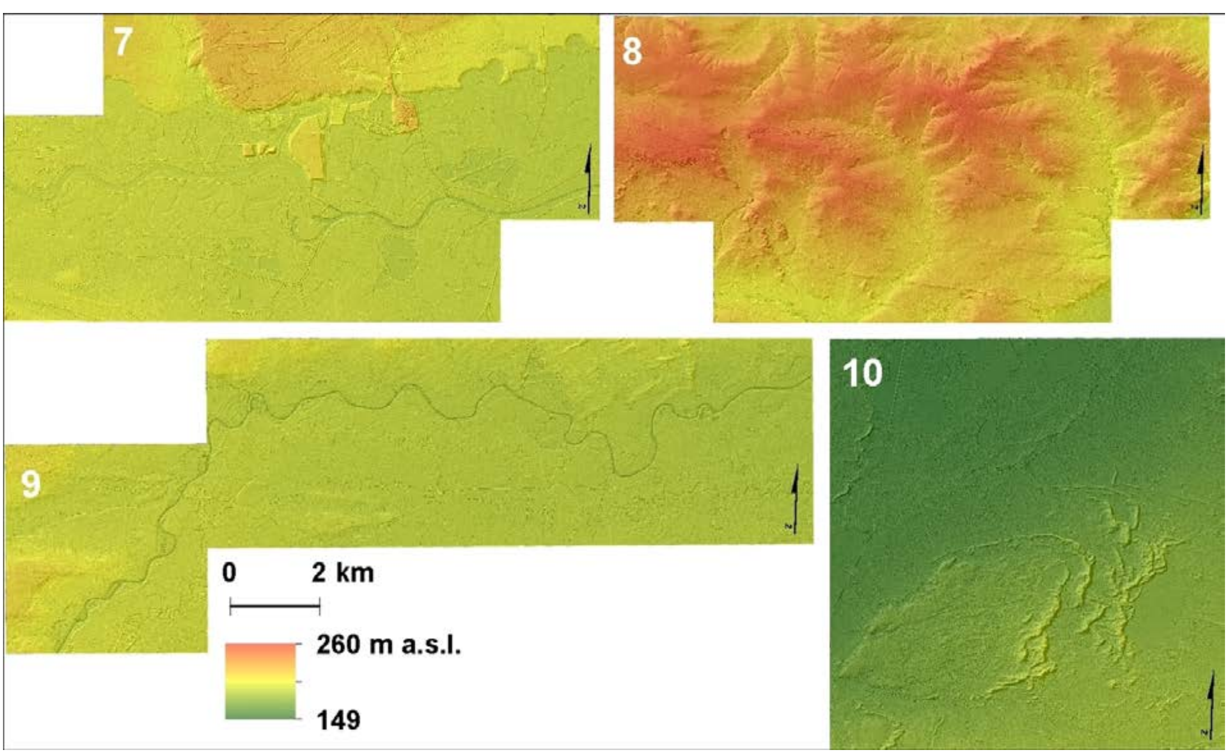

Figure 3: Hypsometry of study areas - intermountain basins

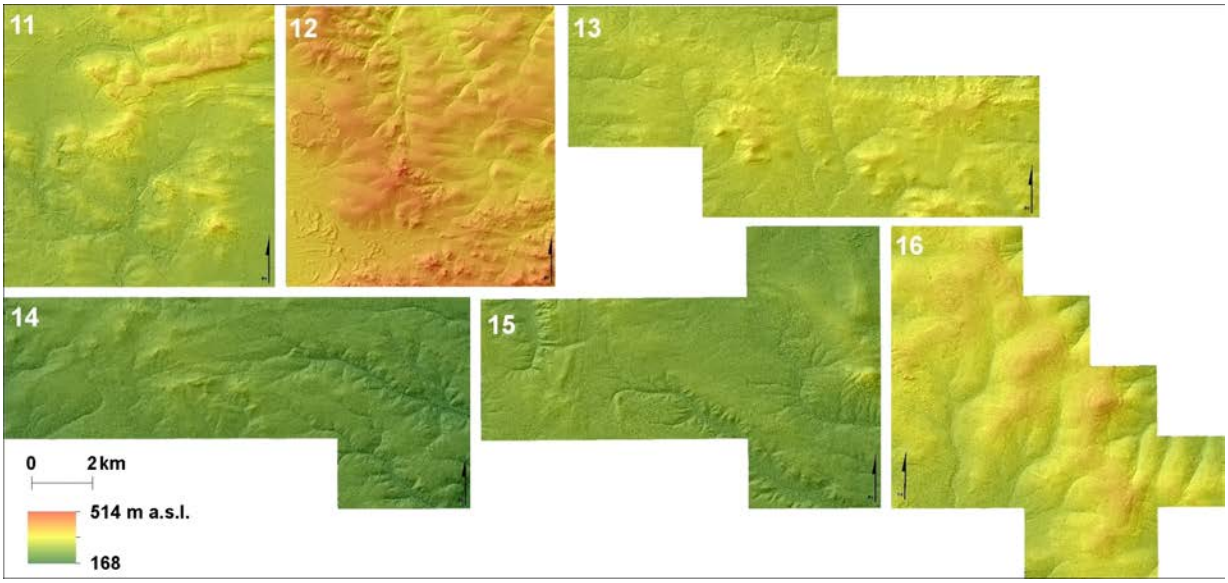

Figure 4: Hypsometry of study areas - uplands

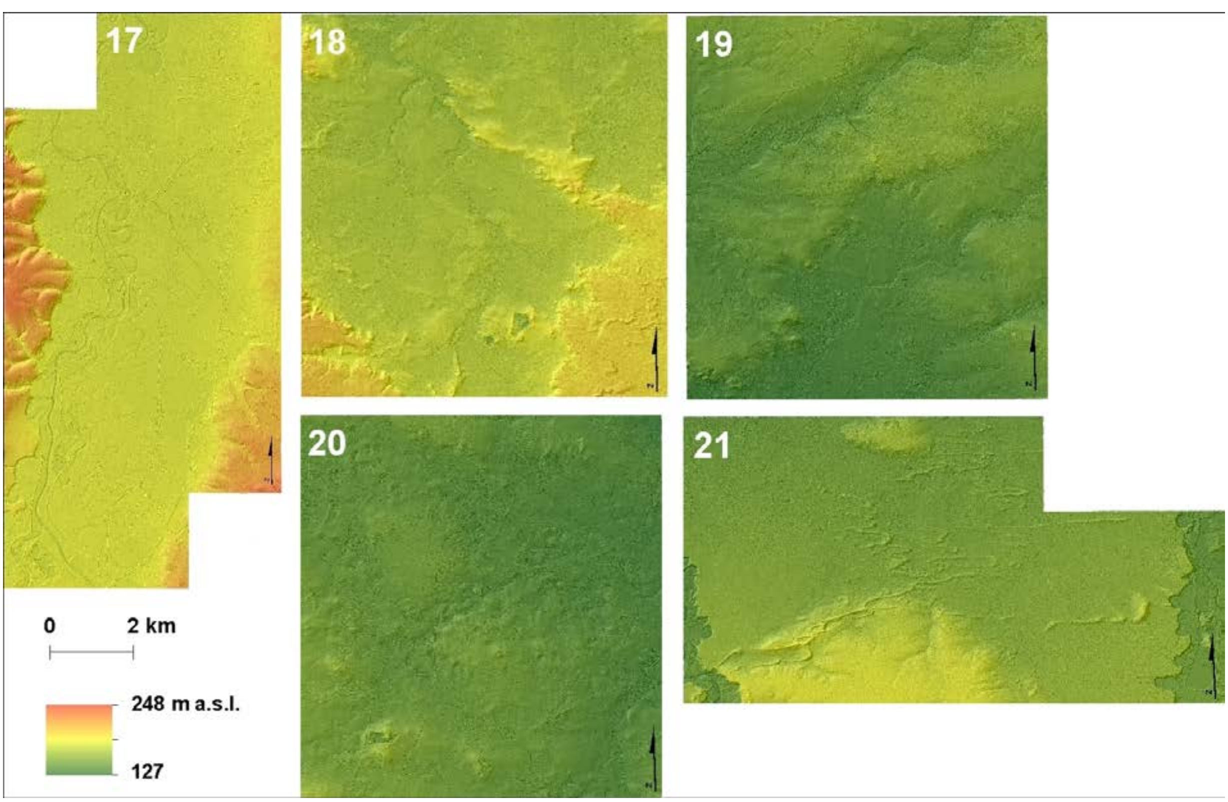

Figure 5: Hypsometry of study areas - lowlands

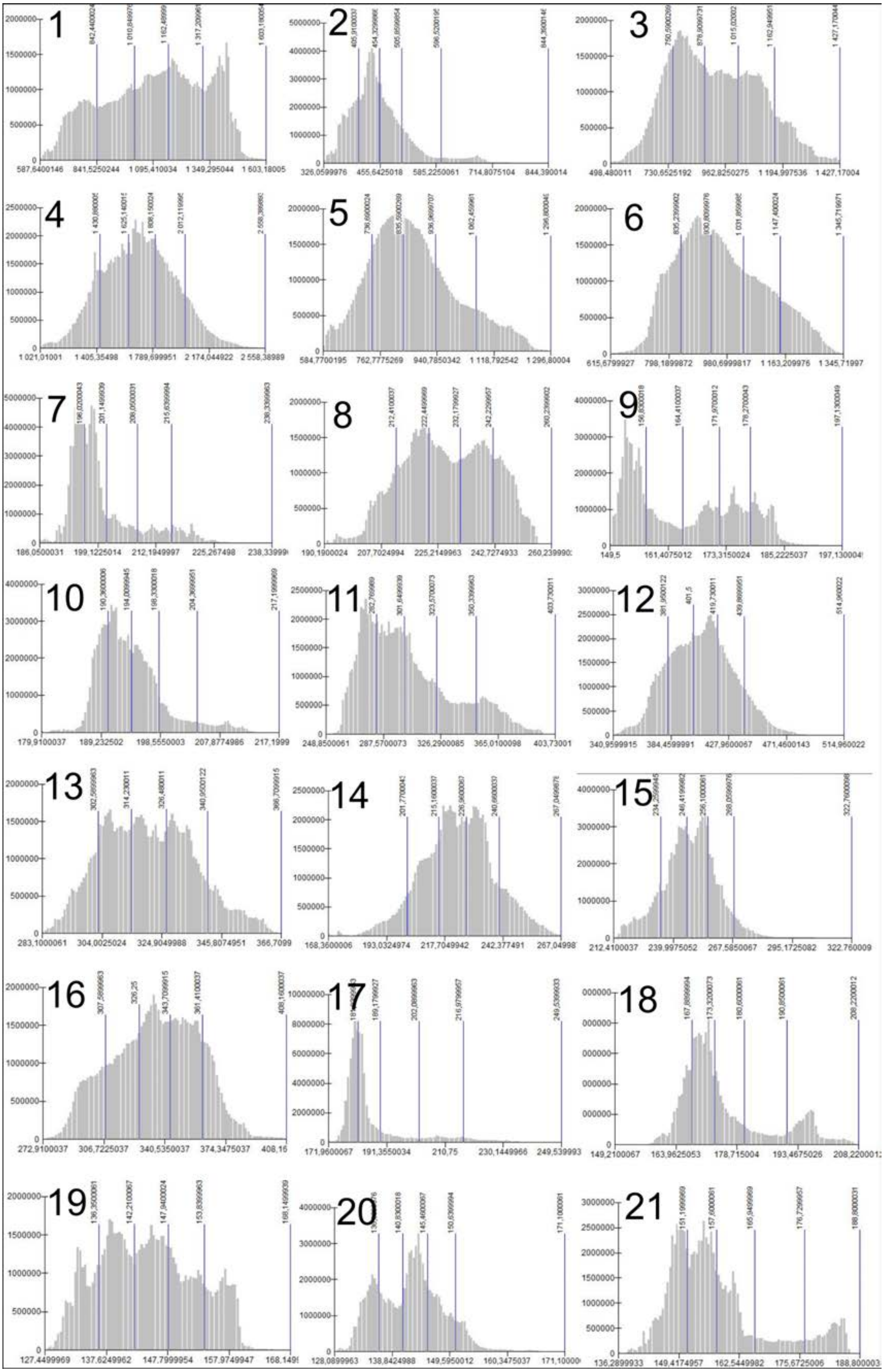

Figure 6: Histograms of DEMs

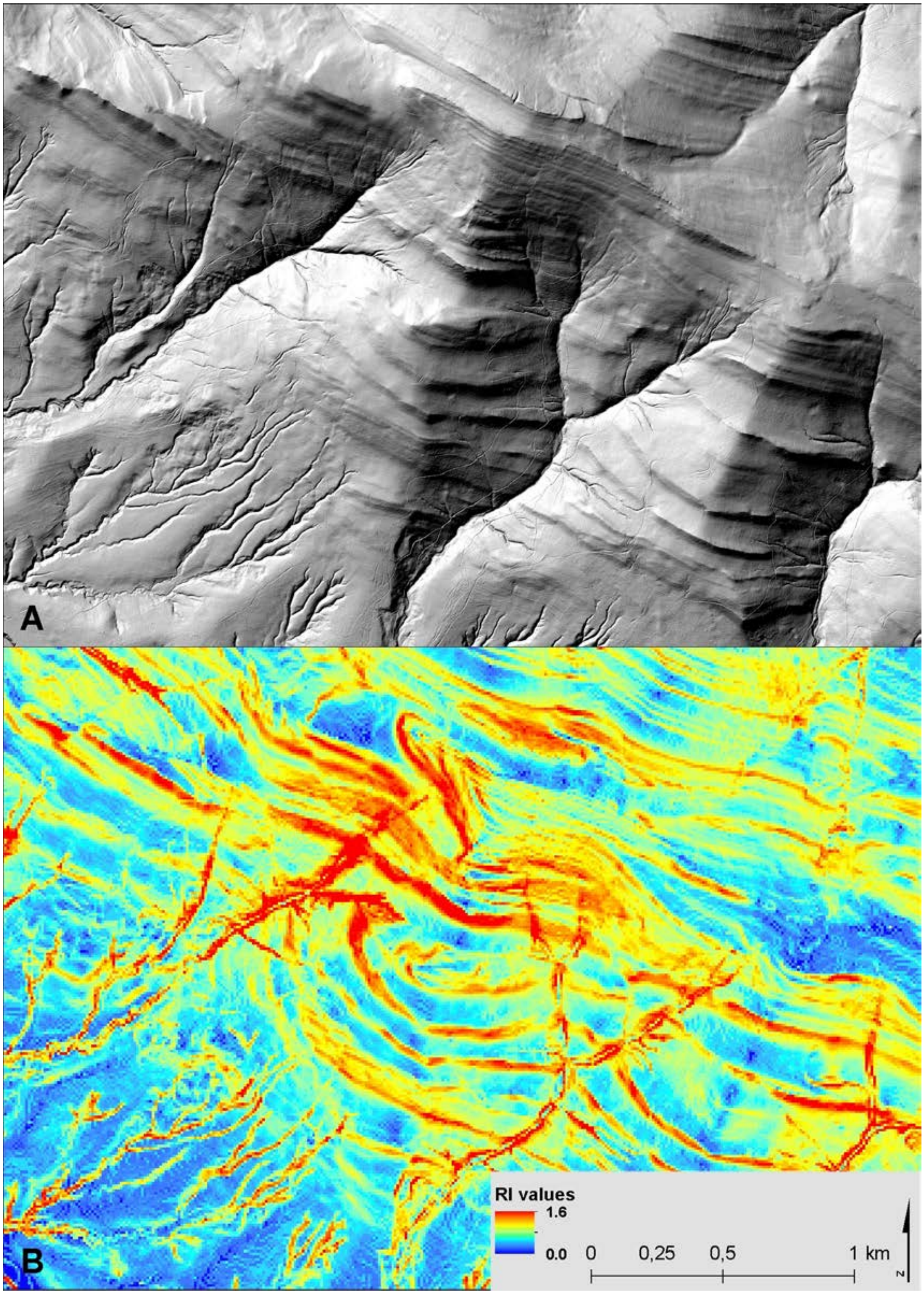

Figure 7: Exemplary of the Relief Index map (B) on the base DEM (A) (fragment of the area nr 5)

I decided to express the Relief Index values in meters (total length of the 1m-interval contour lines) per each square meter of the study area to avoid too large or too small numbers (Table 2). Values of Relief Index show how much complicated the relief is (Figure 7). This quantitative measure describes the degree of surface differentiation with the use of one value. The idea of Relief Index is based on a combination of local relief (number of contour lines and elevational changes) and degree of surface cut (length and shape of the contour lines) with reference to the planar surface area. Common availability of the DEMs and computation simplicity make this index easy to use.

The first step was joining (mosaic) all the 16 asc files for each study area and a lossless conversion to ESRI Grid format for more convenience for further work. From these ESRI Grids 1m-contour lines were generated and their length values were calculated. Next I decided to delete contour lines, which may result from DEM errors. If we know, that horizontal DEM resolution is 1m x 1m, the generated contour lines of ≤ 3 m length are probably errors (we know that perimeter of a circle inscribed within a 1m square is exactly the value of $\pi \approx 3.14$ m). I decided to filter length results by removing the contour lines equal and less than 3 m length. Such prepared contour lines became the basis for further calculations.

The next step was to create grid of squares (10 m × 10 m). These squares have became the basic fields for all calculations: statistics of contour line lengths, local relief (difference between max and min elevation), slopes (change in elevation over the distance between the cell and its neighbours), curvatures (the second derivative of a surface and the slope of the slope), Topographic Wetness Index (ratio between slope and catchment area) and RI values. All calculations were performed in ArcGIS environment, with the use of ArcToolboxes [46].

4 Results and Discussion

4.1 Relief Index

Naturally the highest RI values are related to the mountain areas, where the variability of the hypsometry is the greatest. For the Tatras, the highest mountains in Poland (site 4), the RI values exceeded in places 30 m/m^2, which is associated with almost vertical walls (slopes 81-85°). Also the mean RI value was the highest here, exceeded 0.7 m/m^2. However, due to the greatest diversity of relief, SD value was high (0.6), which suggests a wide variation of RI results compared to other areas, where the value of Relief Index SD does not exceed 0.18, and the average was at 0.11. For the Sudetes area (sites 1 and 3) max RI values fluctuated between 3.9 and 6.4, while for intermountain valley (site 2) was almost 2. For Bieszczady (sites 5-6) there were a more balanced max RI values (1.75 ÷ 2). Generally, for the mountain areas, average RI value was 0.35.

For upland areas of medium-relief (height SD < 30 m) max RI values were 0.9 - 4. The value 4 was associated with the karst area with many residual rocky hills, which inflate maximums (site 12). The average RI values range at 0.06 to 0.10. Low values of RI standard deviation (0.08 ÷ 0.11) indicate a small scatter of the data, which is related to the small fields of the basic calculations.

Areas with low-relief (lowlands and intermountain basins) with height SD < 13 m took maximum RI values between 0.90 to 1.60, and the average RI value 0.05 ÷ 0.08. The differences between the RI values o upland areas, and lowlands and basins are small and result more from the local surface diversity, than the altitude. Although the differences in average RI values between the uplands and lowlands and basins are small (< 0.05), they clearly indicate the relationship with the average slope and local relief values, which well describe these areas (see Table 2).

4.2 Correlation between RI and other DEM derivatives

I decided to see whether there is a relationship between Relief Index values and the other derivatives of the DEMs. I calculated the correlation coefficient (R) between RI and local relief, slopes, planar curvatures and Topographic Wetness Index (TWI).

Table 3 shows the highest correlation values are associated with areas of the most distinctive and diversified relief, and the smallest correlation values with the most aligned areas. For mountain areas the correlation coefficient between RI and local relief amounted to R = 0.84 ÷ 0.96, while for slopes R = 0.79 ÷ 0.94. These very high positive values indicate an almost full compatibility of these three measures.

For the uplands area the correlation coefficient with local relief was lower and took the values R = 0.35 ÷ 0.48 (sites 13-16) and R = 0.73 ÷ 0.80 (sites 11-12). For the analogous areas the correlation coefficient with the slopes amounted to R = 0.25 ÷ 0.37 and R = 0.61 ÷ 0.69. These distinctly different values for the uplands reflect morphology character of the analyzed areas. Sites 11 and 12 are much more diverse in hypsometry and with slopes than the rest of 3 upland areas (see max and mean values of local relief and slopes in Table 2).

The lowest values of the correlation coefficient were recorded for the lowlands and intermountain basin areas. For lowlands correlation with local relief amounted to R = 0.40 ÷ 0.58, and for slopes R = 0.25 ÷ 0.37. The analogous values for the basins were, respectively R = 0.37 ÷ 0.65 (local relief) and R = 0.28 ÷ 0.55 (slopes). It is clear that we

Table 2: RI, local relief, slope and planar curvature statistics

Study areas	Relief Index [m/m^2]					Local relief [m]				Slopes [°]				Planar curvatures			
	min	max	mean	median	SD	min	max	mean	SD	min	max	mean	SD	min	max	mean	SD
Mountains																	
1	0.00	6.42	0.30	0.27	0.18	0.0	60.0	3.2	2.0	0.0	72.9	14.4	7.7	−7908	8604	−32.3	186.2
2	0.00	1.99	0.11	0.09	0.13	0.0	21.8	1.1	1.3	0.0	52.1	4.5	5.8	−2832	2455	−10.4	98.6
3	0.00	3.92	0.30	0.29	0.14	0.0	34.1	3.4	1.7	0.0	58.6	15.5	7.0	−5097	4811	−19.4	146.8
4	0.00	36.67	0.73	0.64	0.59	0.0	196.1	8.1	6.0	0.0	84.8	30.4	13.9	−21928	26114	−93.7	749.7
5	0.00	1.99	0.36	0.33	0.15	0.0	18.6	4.0	1.8	0.0	51.3	17.8	6.9	−2672	2577	−10.3	240.9
6	0.00	1.75	0.34	0.32	0.17	0.0	19.9	3.8	1.9	0.1	52.9	17.0	7.5	−2596	3033	−11.1	240.4
Intermountain basins																	
7	0.00	1.59	0.08	0.00	0.12	0.0	15.8	0.6	0.8	0.0	46.4	1.7	2.9	−2976	2296	−10.4	132.1
8	0.00	0.86	0.06	0.00	0.09	0.0	8.7	0.5	0.4	0.0	27.6	1.9	1.6	−1428	1748	−6.2	73.1
9	0.00	0.96	0.07	0.00	0.11	0.0	9.1	0.5	0.4	0.0	28.4	1.2	1.8	−1486	2104	−7.0	96.1
10	0.00	1.03	0.06	0.00	0.11	0.0	9.1	0.5	0.6	0.0	27.9	1.2	2.1	−1192	1810	−5.9	68.8
Uplands																	
11	0.00	2.02	0.10	0.10	0.11	0.0	12.9	0.9	0.8	0.0	39.9	3.6	3.4	−2335	1987	−8.5	125.5
12	0.00	4.12	0.10	0.10	0.10	0.0	31.5	1.0	0.9	0.0	56.8	4.3	3.4	−4418	7549	−23.8	112.5
13	0.00	1.54	0.06	0.01	0.08	0.0	18.1	0.5	0.4	0.0	49.5	2.1	1.7	−2496	1828	−8.5	64.3
14	0.00	1.29	0.06	0.00	0.09	0.0	10.3	0.5	0.4	0.0	31.6	1.9	1.6	−1524	2133	−7.2	56.6
15	0.00	2.04	0.06	0.00	0.09	0.0	20.0	0.5	0.4	0.0	46.4	1.7	1.7	−2953	2905	−11.5	52.2
16	0.00	0.92	0.08	0.07	0.08	0.0	9.1	0.7	0.3	0.0	28.9	2.7	1.6	−1153	1045	−4.3	54.7
Lowlands																	
17	0.00	1.30	0.07	0.00	0.10	0.0	11.5	0.6	0.7	0.0	39.5	1.7	2.5	−1950	1937	−7.6	106.4
18	0.00	1.57	0.07	0.00	0.11	0.0	19.5	0.5	0.5	0.0	48.1	1.4	2.0	−2387	2785	−10.2	78.0
19	0.00	1.09	0.05	0.00	0.09	0.0	8.4	0.4	0.4	0.0	22.9	1.0	1.1	−1534	1644	−6.2	66.6
20	0.00	1.03	0.05	0.00	0.09	0.0	9.2	0.3	0.3	0.0	33.2	0.9	0.9	−1579	1754	−6.5	54.9
21	0.00	0.90	0.06	0.00	0.10	0.0	9.7	0.5	0.5	0.0	35.2	1.3	2.2	−1275	1369	−5.2	71.4

Table 3: Correlation coefficient (R)* between RI and local relief, slopes, planar curvatures and Topographic Wetness Index

Study areas	Number of observations	RI and local relief	RI and slopes	RI and curvatures	RI and TWI
Mountains					
1	817175	0.95	0.92	−0.01	−0.24
2	825943	0.84	0.82	−0.04	−0.30
3	826457	0.96	0.94	−0.03	−0.21
4	841608	0.94	0.79	0.05	−0.35
5	843920	0.95	0.88	−0.13	−0.14
6	838909	0.94	0.90	−0.13	−0.17
mean:	832335	0.93	0.87	−0.05	−0.23
Intermountain basins					
7	828539	0.65	0.55	0.03	−0.29
8	828671	0.48	0.34	0.05	−0.10
9	822379	0.37	0.28	0.03	−0.17
10	828494	0.51	0.42	0.01	−0.16
mean:	827020	0.50	0.40	0.01	−0.18
Uplands					
11	821766	0.73	0.61	0.01	−0.24
12	820268	0.80	0.69	0.08	−0.24
13	818597	0.48	0.37	−0.01	−0.11
14	809243	0.41	0.34	−0.02	−0.09
15	811106	0.35	0.29	0.00	−0.09
16	809344	0.36	0.25	0.01	−0.06
mean:	815054	0.52	0.42	0.01	−0.14
Lowlands					
17	825363	0.58	0.48	0.02	−0.26
18	819332	0.40	0.27	0.00	−0.14
19	809220	0.40	0.27	−0.02	−0.11
20	813581	0.41	0.22	0.00	−0.11
21	805617	0.48	0.40	0.00	−0.16
mean:	814622	0.45	0.33	0.00	−0.16

* Due to the large number of observations (on average 822168) the significance level was $p<0.001$

are dealing with local variation of the correlation degree associated with the nature of the surface relief (*e.g.* higher correlation values for site 7 - see Table 2).

The situation is quite different for correlations between Relief Index and planar curvatures and TWI. Relationship between RI and planar curvatures is statistically insignificant (they were slightly above or below zero). This is due probably to the fact surface curvature at a point is the curvature of a line formed by the intersection of the surface with a plane with a specific orientation passing through this point. The value of the curvature is reciprocal of the radius of the curve - the larger the radius, the smaller the curvature value (a gentle curve has small curvature and a tight curve has large curvature value). The units of the curvature are radians per linear unit (the unit of the spatial reference of the raster) [49]. If, however, it was calculated sinuosity ratio of the contour lines we could be expected significant correlation. Unfortunately, with so much data it was not possible to count.

Correlations with TWI are also negligible. Only for mountain (sites 2 and 4) there are values of 0.30 and 0.35 which indicates low negative correlation. The lack of relationship may results from fact, that TWI values are higher for pixels with lower slopes. This means that TWI primarily reflects accumulation processes [49].

4.3 Relief Index classes

On the basis of the Relief Index results from the 21 analyzed test areas and the results of the relationships with the local relief and slopes it can be pre propose the following arbitrary Relief Index classes (Table 4):

Class 1 (RI = < 0.05) - there are areas with the least diversified relief, flat or almost flat, usually aligned wide river valleys and lowland areas with very low local relief values.

Class 2 (RI = 0.06 ÷ 0.09) - it is already clearly marked relief, mainly covers areas of intermountain basins and uplands of low- and medium-relief (height SD 5 ÷ 30 m) and slopes < 3°.

Class 3 (RI = 0.10 ÷ 0.40) - it is highly varied relief foothills and low mountains, with large local differences in height (height SD 60 ÷ 200 m) and the average slopes of up to 20°.

Class 4 (RI = > 0.40) - describes the areas with the highest elevation amplitude (height SD > 200 m), there are the high mountain landscapes with alpine features and vertical rock walls.

Table 4: Classes of Relief Index

Relief Index class	The average value of		
	Relief Index [m/m^2]	Local relief [m]	Slopes [°]
1	< 0.05	< 0.4	< 1°
2	0.06 ÷ 0.09	0.5 ÷ 0.8	1 ÷ 3°
3	0.10 ÷ 0.40	0.9 ÷ 4.5	3 ÷ 20°
4	0.40 <	4.6 <	20° <

These proposed subdivisions are approximate and refer to the analyzed areas. The presented RI classes are contractual. Much more important are RI values between 0.05 and 0.40 m/m^2, which rapid and simply show how varied the relief is. Undoubtedly, it is lack of analysis of the younglacial landscapes (*e.g.* from the northern Poland), or flatted and cut by network of the meandering riverbeds, the author intends to address it in the near future.

4.4 Relief Index vs DEM resolution and basic fields

While I analyse an area using maps or digital data, there is always a question about the scale. In case of working with DEM I should rather speak about horizontal resolution and vertical accuracy, which determine DEMs precision (i.e. the least landform to identify). At this point, I decided to verify whether the DEM resolution and size of the basic fields significantly affect the results of the RI values. For this purpose, I chose the test area (2 km × 2 km) from area nr 4 and converted 1m-DEM to different resolution DEMs: 10 m × 10 m, 25 m × 25 m, 50 m × 50 m (calculations were also done for 100m-DEM, but they did not provide satisfactory results). Relief Index values were calculated exactly in the same way for each DEM as the previous calculations (see 3. Data and methods). The only difference was the initial filtering of the contour lines: from 10m-DEM I removed contour lines with the length of ≤ 31.25 m, from 25m-DEM with the length of ≤ 78.5 m and from 50m-DEM with the length of ≤ 157 m. Of course, this action has affected the generalization of the spatial image.

Figure 8 shows that the higher is the DEM resolution, the more accurate is the relief representation. This is confirmed by Table 5, where RI values range from 7.5 (1m-DEM) to 1.8 (50m-DEM). Similar situation occurs for basic fields 50m × 50m (from 2.4 for 1m-DEM to 1.5 for 50m-DEM). However, max RI values are relevant only in regards to small landforms. When we look at the average RI values, we will see they are at a similar level (RI = 0.6 ÷ 0.7). This means that despite the various DEM resolutions, the RI values well reflect general relief diversity, *i.e.* the statistical character of the topography.

The best RI values distribution was shown for 1m-DEM (Figure 8A). There are artifacts in the other three pictures (Figure 8B-8D). There are parallel light blue horizontal and vertical lines (Figure 8B, 8C). In addition, the RI values were significantly lower, where they should be maxima (white arrows in Figure 8D). The above errors are the result of using an incorrect (too small) size of the basic field compared to the resolution of the used DEMs. Such situation isn't appearing, if we increase the size of the basic field (see Figure 9B-9D). So, one should to remember the size of the basic field is always greater than, the size of the DEM grid.

5 Conclusions

The Relief Index provides a rapid and objective measure of land surface irregularity and appears adaptable to a wide range of situations. The total length of the contour lines occurred on the surface unit (1m^2) clearly reflects the nature of the surface. The best input DEM for these calculations is LiDAR, because of high vertical and horizontal accuracy.

Results of the executed calculations demonstrated that there is a significant correlation between RI and the lo-

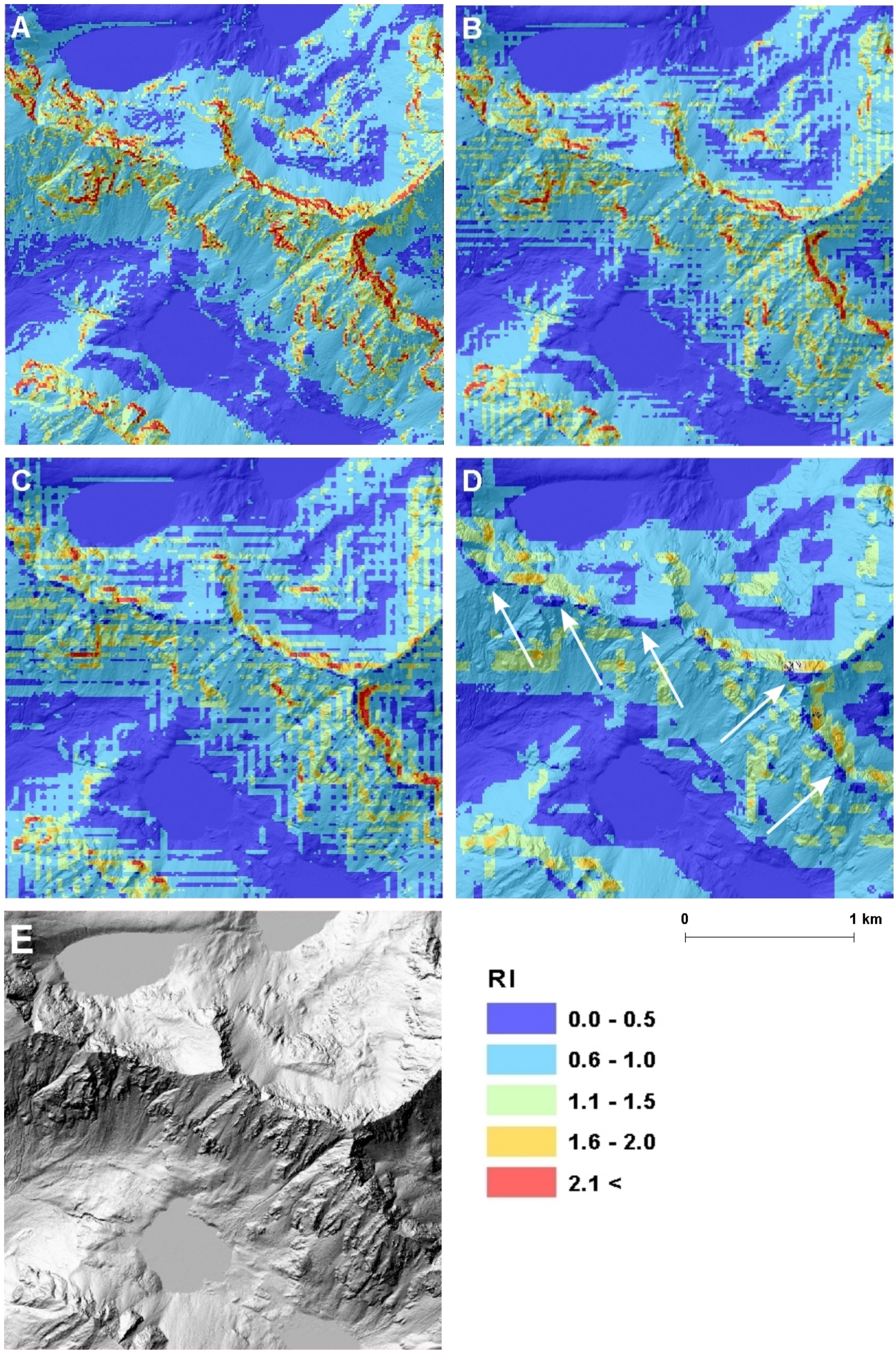

Figure 8: Relief Index in the 10m × 10m basic fields: A 1m-DEM, B 10m-DEM, C 25m-DEM, D 50m-DEM, E hillshade relief

Table 5: Relief Index in different DEM resolutions and basic fields

DEM resolution [m]	Relief Index [m/m^2]							
	Basic field 10 m × 10 m				Basic field 50 m × 50 m			
	min	max	mean	SD	min	max	mean	SD
1 × 1	0.0	7.5	0.7	0.5	0.0	2.4	0.7	0.4
10 × 10	0.0	3.7	0.6	0.4	0.0	2.1	0.7	0.4
25 × 25	0.0	2.9	0.6	0.4	0.0	1.9	0.6	0.3
50 × 50	0.0	1.8	0.6	0.4	0.0	1.5	0.6	0.3

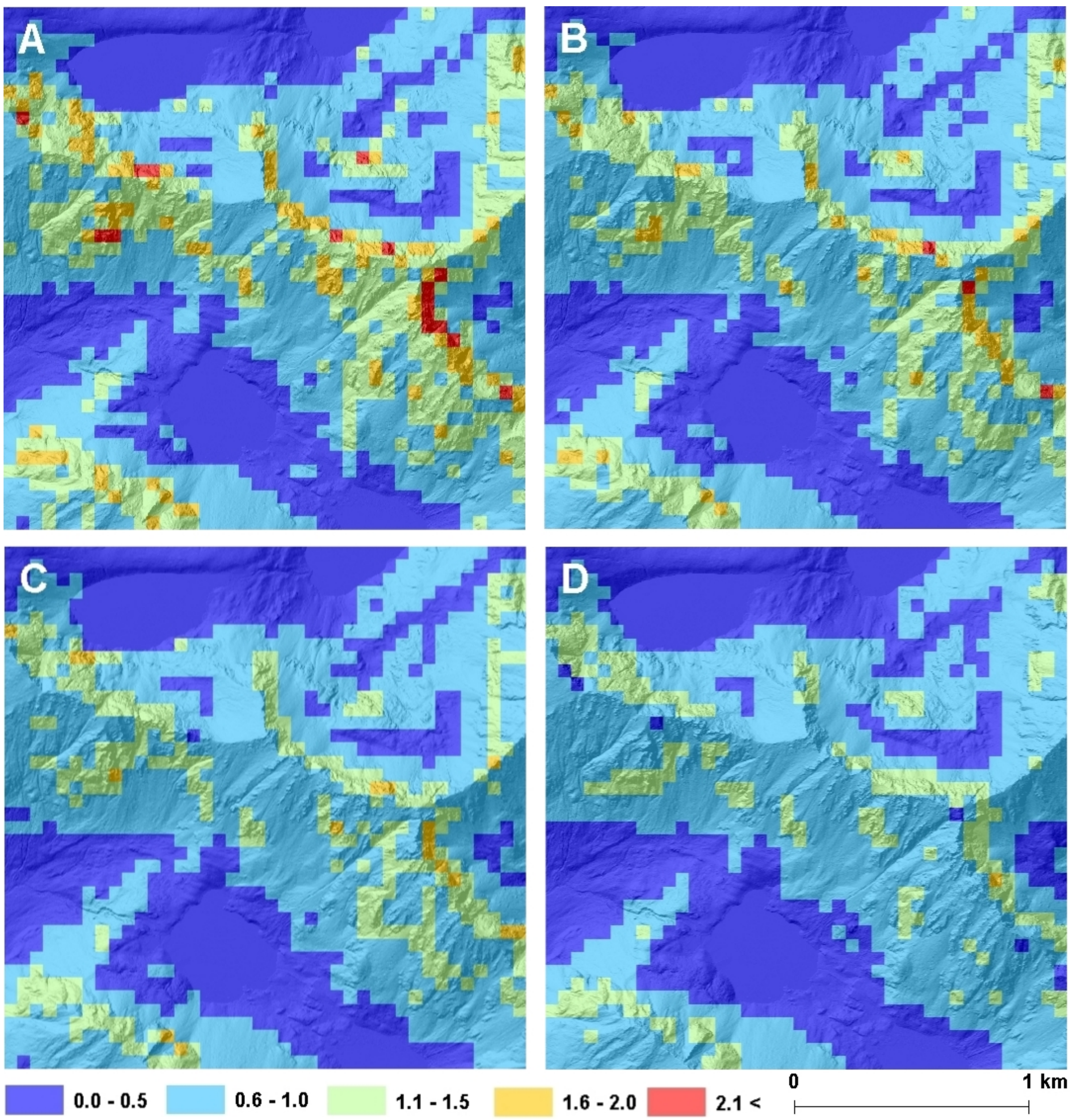

Figure 9: Relief Index in the 50m × 50m basic fields: A 1m-DEM, B 10m-DEM, C 25m-DEM, D 50m-DEM

cal relief and slopes, but there is no correlation between RI and planar curvatures and TWI. According to Guilford [50] high and very high correlation coefficient (R ≈ 0.93) of the relationship between RI and local relief can be observed for mountains. The same correlation was moderate, but substantial for the other areas: uplands R ≈ 0.52, intermountain basins R ≈ 0.50 and lowlands R ≈ 0.45. Correlation coefficient between RI and slopes was less than the mentioned above 0.02 ÷ 0.19, but it was still very high correlation for mountains. For uplands, intermountain basins and lowlands the correlations were low and moderate (Table 3).

I distinguished 4 classes of the Relief Index that classify earth surface due to variability of the relief. Class 1 is the least diverse and flat areas; class 2 is the upland areas with the ridge-lines and plateaus; class 3 includes the foothills and low mountains, and class 4 are the highest mountains. Certainly RI calculations should be supplement with areas that show another type of relief: flatted lowlands of central Poland cut by network of the meandering riverbeds, young-glacial landscapes of the northern Poland - hilly and undulating lakelands and coastal region. The analysis of these areas is in the plans in the near future. This will help better specify Relief Index classes.

The influence of DEM resolution on the RI calculations was investigated and one should said that the change DEM resolution did not negatively affect the final RI values and their spatial distribution. You just have to remember to adjust the appropriate size of the basic calculation fields to the DEM resolution.

In conclusion, RI is based on the simple calculation: the ratio of the total length of the contours traversing a given planar area. Despite the passage of time and the development of computer techniques, we still use the contour lines as a simple and understandable method of representing the altitude difference of the topography. So, one can use Relief Index for the following reasons: 1) clearness the assumptions - use of contours as accepted and effective method reflecting morphology; 2) easily calculated and requiring minimal input data (only DEM); 3) good correlation with primary morphometric properties (local relief and slopes); and 4) the possibility of easy comparisons of the computation results between different areas.

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