

This paper is a part of *Climate and environmental changes recorded in loess covers* (eds. Maria Łanczont, Przemysław Mroczek and Wojciech Granoszewski)

Geomorphometric features and distribution of the loess covers in the Lublin Region

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Gawrysiak, L., Kołodyńska-Gawrysiak, R., 2023. Geomorphometric features and distribution of the loess covers in the Lublin Region. *Geological Quarterly*, 2023, 67: 53; <http://dx.doi.org/10.7306/gq.1723>

The study presents a new, accurate map of the distribution of loess patches in eastern Poland, developed on the basis of publications, geological maps and a high-resolution (1 m) digital terrain model (DTM). Seventy-two lobes were mapped, for the surfaces of which basic morphometric characteristics (mean height, local relief, slope, slope range) were calculated based on the DTM. The morphology of the patches was portrayed via geomorphons-geomorphometric features representing 10 basic landform elements. A map of the geomorphons and their morphometric features were used to analyse the similarity of the patches' morphology using Kendall's Tau correlation and hierarchical clustering, represented by a dendrogram and heat map. As a result, 3 groups of patches with different morphometric features were distinguished. The results obtained characterize in detail the morphological differentiation of loess covers of eastern Poland and will form the basis for further studies determining the evolution of loess cover relief.

Key words: loess covers, geomorphometric features, geomorphons, loess relief, similarity.

INTRODUCTION

The distribution of loess covers has been much studied, starting with maps covering individual regions of Poland (Moskal-del Hoyo, 2021), including the Lublin Upland (Maruszczak, 1961, 1963; Dolecki et al., 2004), the entire area of Poland (Maruszczak, 1987, 1991, 1995, 2001; Jersak et al., 1992), of Europe (Haase et al., 2007; Lehmkühl et al., 2021), of some European regions (Lindner et al., 2017; Lehmkühl et al., 2018) and of the world (Pécsi, 1990; Li et al., 2020a). The most detailed information on the distribution of loess covers can be found on geological maps (Detailed Geological Map of Poland 1:50,000) where, using lithological criteria, the following are distinguished: loess, sandy loess, loamy loess, sandy loam, sandy loam and valley loess on river terraces. Geological maps at smaller scales (1:300,000) distinguish only 2 categories: loess and sandy loess, while at the overview scale (1:500,000) there are also 2 categories: loess and loess-like sediments (Marks et al., 2006). Loess cover is also distinguished on geomorphological maps. In the study area, these are the Lublin sheet of the Overview Geomorphological Map of Poland at 1:500,000 scale

(Gilewska et al., 1980). So far, the only study that distinguishes sets of relief forms within loess patches is the map *Le relief des terrains de loess sur le Plateau de Lublin* by Maruszczak (1961), on which he distinguished 3 sets of relief forms: high levels, slopes and river terraces.

Comprehensive studies of the relief of loess areas in the Lublin Upland were carried out at overview scales allowing a general characterization of the morphology of the loess patches (Maruszczak, 1961, 1991) and the recognition of a set of forms characteristic of loess areas (Maruszczak, 1958; Kęsik, 1960). Detailed studies of loess relief have most often concerned the density of seminatural gullies (e.g., Buraczyński, 1972, 1977; Maruszczak, 1973; Józefaciuk and Józefaciuk, 1992; Gawrysiak and Harasimiuk, 2012), and of road gullies (Józefaciuk and Józefaciuk, 1992; Kołodyńska-Gawrysiak et al., 2011). Studies have also been carried out on the genesis, morphometry, distribution and evolution of closed depressions (Maruszczak, 1954; Kołodyńska-Gawrysiak and Chabudziński, 2012, 2014; Kołodyńska-Gawrysiak and Poesen, 2017; Kołodyńska-Gawrysiak et al., 2018, 2019; Kołodyńska-Gawrysiak, 2019a) and the role of piping in the development of the relief of loess areas (e.g., Gardziel and Rodzik, 2005; Rodzik, 2008). In southwestern Poland, studies of loess relief have been carried out only on the Głubczycka Plateau (Jary, 1991; Jary and Kida, 2002), in the Opole region (Kida, 1996), and the Trzebnickie Hills and Niemczańskie Hills (Jary and Kida, 2002). In other regions of the world, geomorphometric studies of loess relief have been conducted mainly in China (e.g., Xiong et al., 2014, 2018; Du et al., 2019; Ding et al., 2021; Wei et al., 2021), and, less fre-

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Received: April 24, 2023; accepted December 23, 2024; first published online: January 7, 2024

quently, with the use of GIS techniques, in Europe (e.g., Popov et al., 2012).

The use of GIS and digital environmental data has created new opportunities to study landforms quantitatively, including the development of methods for classifying loess landforms (Xiong et al., 2018; Du et al., 2019), the analysis of extraction derivatives from Digital Terrain Models (DTMs) of loess landforms (Fang et al., 2008; Hu et al., 2020) and of geomorphic processes (Cao et al., 2013; Xiong et al., 2014; Feng et al., 2020), and the creation of indices (Pike and Wilson, 1971; Jiang et al., 2021; Yuan et al., 2020). Currently, classification methods can be divided into 2 groups based on the classification of cells and, now becoming more popular, objects (Xiong et al., 2018; Ding et al., 2021; Wei et al., 2021; Yuan et al., 2022) via object-oriented image analysis and deep learning for landform extraction and groupings (Li et al., 2020b).

This study accurately maps the distribution of loess patches on the Lublin Upland and, quantitatively and geomorphometrically, characterizes the patches using GIS technology. Based on these characteristics, an elaborate typology of patches is constructed, distinguishing the main types with their unique relief parameters. Then, the spatial arrangement of the patches of each type is analysed to identify the main factors determining their situation.

MATERIALS AND METHODS

The study was based on the geomorphological maps developed by Maruszczak (1961, 1963), with constraints from sheets of the Detailed Geological Map of Poland at 1:50,000, and a digital terrain model (DTM) with a resolution of 1 x 1 m and its derivative: a shaded relief map, for visual analysis and interpretation. Checking and correction of the boundaries of patches distinguished in earlier studies took place. More significant changes arising from Maruszczak's maps concerned only the neighbourhood of the lower Huczwa Valley, where a number of small, isolated patches were newly distinguished. For this area we used the mapping of Dolecki et al. (2004) and Dolecki (1999, 2010) and discussed the patch boundaries with geomorphologists working in this area. For the 72 patches recognized (Fig. 1), a map of geomorphons-geomorphometric objects mapped using 10 main topographic elements: flat, summit, ridge, shoulder, spur, slope, hollow, footslope, valley and depression – was generated on the basis of a 1 x 1 m DTM (Jasiewicz and Stepinski, 2013). Morphometric characteristics including area, average elevation (m a.s.l.), local relief within the patch (m), average slope (in degrees), range of slopes (in degrees) and proportions of each geomorphon type were calculated for the patches studied. The de-

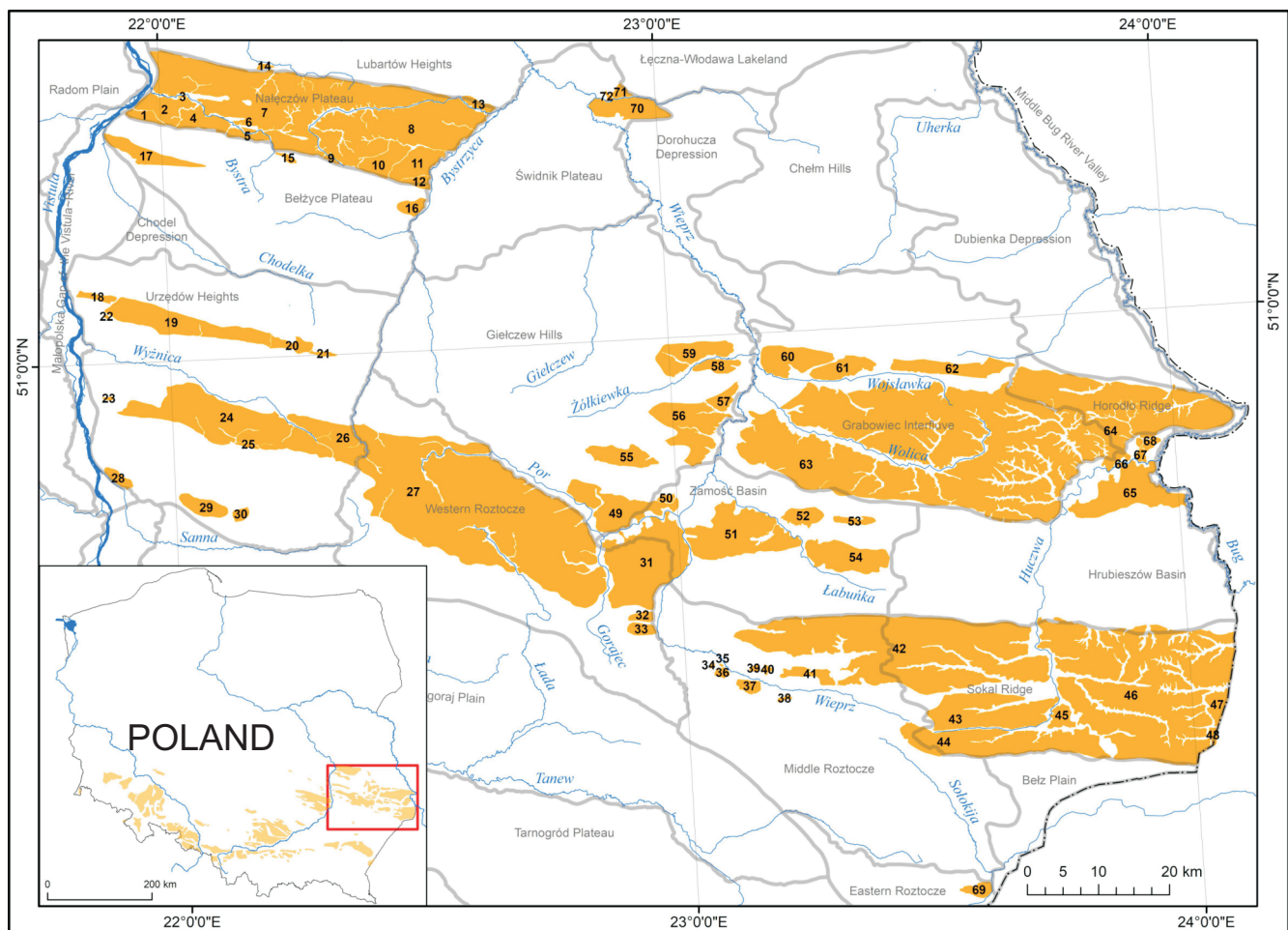


Fig. 1. Distribution of loess patches (numbered from 1–72) against the background of mesoregion boundaries (after Gawrysiak and Kociuba, 2023, modified and completed) according to the physical geographical divisions of Solon (2018)

tailed characteristics of four morphometric parameters (mean height, local relief, mean slope and slope range) and the distributions of their values were summarized in charts. For each patch, the proportion of area of each of the ten types of geomorphon was calculated, which, together with the four morphometric parameters, were used as 14 variables for calculating the Kendall's Tau correlation matrix (Kendall, 1948) between all patches. The distribution of correlations and clustering was visualized in the form of a dendrogram (Ward method) and heat map. A similarity analysis of the relief of the patches was carried out, which made it possible to distinguish three groups of patches with similar morphometric features (Fig. 2). Basic statistics of correlation between the patches were used to characterize the variation of similarity within the groups distinguished. In order to visualize the variation in relief of individual patches, sample geomorphon maps were compiled.

RESULTS

Loess covers 3,384 km² of the Lublin Upland, which is 29.96% of its area. It forms isolated patches, usually clearly distinguishable in the relief, and in some instances covering al-

most entire mesoregions (Fig. 1). In the study area, 72 loess patches were mapped (Fig. 1–4). The average size of a patch is 47 km², though the largest (Grabowiec Interfluve – Horodlo Ridge) reaches 611.4 km² (Tables 1 and 2). The distribution of values of the local relief of individual patches is nearly 150 m, with the average height of all patches being 238.8 m a.s.l. (Fig. 5). Similarly, the local relief within the patches varies strongly and reaches a maximum of 148.8 m, with an average of 72.7 m. Average slopes within individual lobes range from 2.24 to 15.95°, with an average for all lobes of 4.44°. The proportion of individual geomorphon types within the patches varies greatly (Table 3 and Figs. 3, 4). The largest areas are occupied by slopes, the proportion of which in the patches ranges from 19.04 to 65.48%, with a total of 43.38%. The second type in terms of area proportion is the spur geomorphon, which occupies a total of 18.25% of the area of all patches, and within individual patches varies from 3.99 to 36.42%. The valley proportion (7.67% of the patches' area) ranges from 1.05–12.43%. Hollow and ridge elements have a similar total proportion of the patch area (9.44 and 8.53%, respectively) and slightly different ranges of values within individual patches, 2.55–15.84% and 2.09–22.73%, respectively. Flat elements, at 4.76% of the patches' area have a large scatter among individual patches

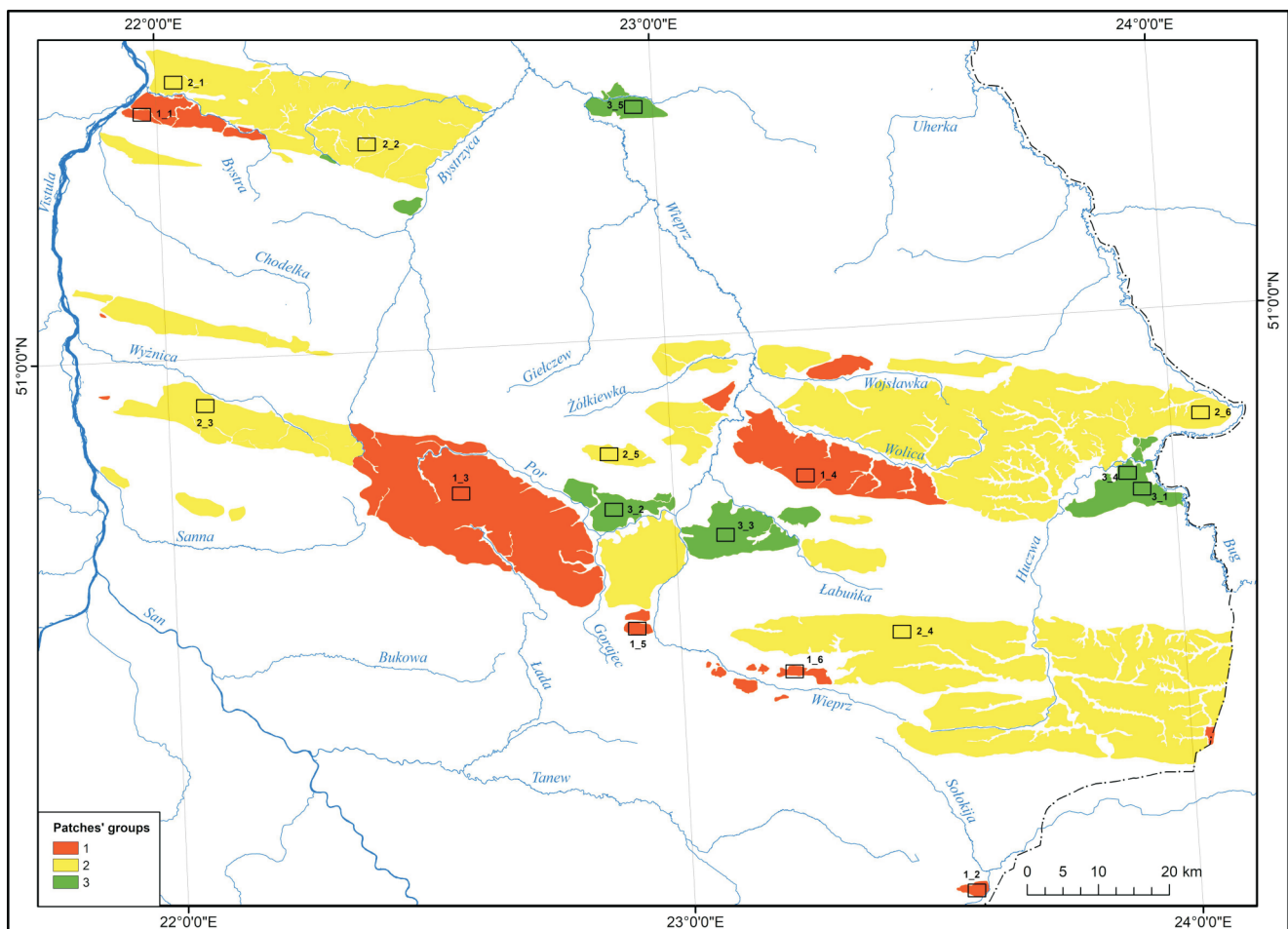


Fig. 2. Loess patches classified into groups on the basis of geomorphon proportions and selected morphometric features

Small boxes (1_1, 1_2, etc.) indicate the location of sample geomorphon maps showing different types of surface shown on Figure 6

Table 1

Detailed morphometric characteristics of the loess patches studied

1	2	Share of geomorphons										Morphometric parameters			
		3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	5.93	0.11	1.15	22.73	0.23	30.57	26.76	7.39	0.27	8.47	2.31	183.5	93.6	13.0	73.2
2	19.51	0.03	1.01	20.79	0.62	28.93	28.38	8.91	0.23	9.09	2.01	189.7	96.8	12.2	80.4
3	0.35	0.00	0.99	18.17	0.00	32.67	38.96	5.58	0.00	3.60	0.03	167.9	52.0	11.9	57.1
4	15.67	0.47	0.88	15.02	1.60	26.35	36.05	8.96	0.89	8.20	1.59	189.5	74.8	8.4	74.6
5	5.87	0.16	1.24	16.59	0.82	27.71	35.24	8.75	0.47	7.39	1.63	193.1	56.6	9.3	69.6
6	0.98	0.68	1.75	15.07	1.49	25.03	38.08	7.79	1.97	7.47	0.68	188.7	49.8	9.6	59.6
7	222.27	2.27	0.88	12.00	3.04	18.93	38.98	10.02	3.47	9.54	0.86	202.8	111.2	5.6	78.4
8	131.11	2.95	0.87	9.40	4.22	15.94	41.17	10.87	4.71	9.42	0.48	212.1	86.1	3.9	78.8
9	1.27	14.05	0.83	9.89	8.05	11.58	30.77	5.92	11.48	7.33	0.11	225.5	15.3	2.9	49.3
10	17.96	2.11	0.66	9.57	3.89	17.54	42.30	10.82	3.68	8.97	0.46	224.6	67.3	4.3	77.0
11	21.97	2.47	1.16	10.54	3.98	16.84	37.85	12.08	3.55	11.01	0.52	209.6	66.5	4.7	76.8
12	5.03	6.49	0.84	7.51	5.43	15.59	41.26	9.96	5.13	7.37	0.40	199.9	52.1	4.0	62.3
13	4.89	11.08	0.56	8.16	3.97	15.96	44.52	7.50	3.33	4.08	0.83	188.6	41.7	4.9	71.5
14	1.26	6.09	0.21	3.23	7.40	9.60	65.48	3.57	3.36	1.05	0.03	174.5	27.9	2.9	37.1
15	1.73	4.35	0.78	7.24	6.00	17.53	49.72	6.37	3.46	3.95	0.62	202.8	43.3	4.9	62.7
16	6.82	13.36	0.18	3.23	9.30	7.71	49.20	5.63	7.76	3.31	0.30	202.5	49.7	2.4	58.1
17	20.79	9.41	0.55	12.40	6.40	16.95	36.98	6.07	3.90	5.88	1.45	201.9	106.7	6.8	79.9
18	4.57	5.37	0.42	10.65	5.16	16.92	42.83	7.20	3.92	6.70	0.82	200.8	79.3	5.4	68.9
19	58.50	5.22	0.42	8.12	5.71	16.01	47.55	6.53	3.55	5.81	1.07	215.9	94.6	4.7	73.9
20	8.46	2.49	0.29	7.07	4.21	18.06	49.13	7.66	2.87	7.51	0.71	235.9	65.6	4.9	73.0
21	1.84	2.21	0.44	6.32	3.24	16.09	57.98	7.61	1.89	4.06	0.16	224.4	36.8	4.3	68.0
22	0.34	0.14	2.58	17.87	0.01	10.74	46.26	10.29	1.84	10.01	0.26	200.6	55.5	8.7	55.0
23	0.63	0.02	1.07	14.50	0.90	21.68	35.89	11.17	0.41	12.43	1.92	205.9	73.2	10.4	58.9
24	119.36	3.32	0.44	9.47	4.63	19.47	42.20	8.44	3.57	7.50	0.97	236.7	119.7	5.3	78.1
25	1.88	3.93	0.22	7.87	5.26	17.75	45.28	8.20	4.02	6.97	0.51	221.8	43.0	4.1	61.6
26	34.25	2.47	0.44	7.26	3.17	18.34	47.81	9.81	2.77	7.43	0.51	257.7	90.7	4.3	69.7
27	447.19	0.35	0.54	9.63	0.71	24.16	44.65	9.86	0.74	8.25	1.12	277.0	130.2	7.7	78.6
28	5.78	2.83	0.58	9.23	3.15	17.50	49.50	8.13	2.43	6.07	0.56	186.8	68.1	6.9	70.9
29	13.46	3.79	0.34	9.13	4.58	18.14	47.24	7.09	3.02	5.67	1.00	242.3	84.6	6.0	68.9
30	3.46	1.65	0.40	9.32	2.35	24.13	45.90	7.93	1.08	6.25	0.99	226.4	62.9	6.9	70.0
31	103.24	12.39	0.39	8.86	3.77	19.08	36.67	7.38	4.12	6.42	0.92	242.8	139.8	7.1	76.1
32	4.05	0.00	0.31	10.98	0.00	27.01	44.69	9.31	0.09	6.36	1.25	268.3	108.2	13.5	71.5
33	5.85	0.00	0.52	13.85	0.02	28.91	40.02	8.50	0.01	6.50	1.67	280.4	121.6	13.9	70.3
34	0.49	0.00	0.46	15.08	0.00	36.42	31.09	9.78	0.00	6.10	1.07	289.1	76.1	12.6	55.4
35	0.15	0.00	0.01	14.67	0.00	30.68	30.91	15.84	1.32	6.50	0.08	261.3	46.5	10.5	59.2
36	2.16	0.00	0.39	15.85	0.00	28.49	35.96	10.13	0.00	7.17	2.03	303.2	109.1	15.9	69.0
37	5.21	0.00	0.45	14.51	0.02	29.15	37.56	8.59	0.01	7.76	1.95	302.9	111.5	14.2	72.3
38	0.97	0.00	0.51	12.40	0.01	21.51	51.59	9.57	0.00	4.26	0.15	314.7	86.1	11.4	65.5
39	0.98	0.00	0.65	12.83	0.00	24.91	39.50	10.69	0.01	10.81	0.58	311.3	76.8	10.2	60.5
40	1.25	0.00	0.33	13.94	0.00	31.78	34.75	7.77	0.00	8.48	2.95	296.2	75.0	14.3	69.9
41	9.82	0.18	0.79	10.17	0.68	23.58	45.79	10.41	0.51	7.23	0.66	298.2	77.8	6.7	65.2
42	294.15	0.88	0.53	8.16	1.20	20.89	47.42	10.73	1.05	8.65	0.47	267.1	149.1	5.6	71.7
43	68.72	1.66	0.59	8.61	1.87	20.26	45.67	10.47	1.65	8.78	0.44	247.7	100.9	5.3	70.7
44	88.47	6.10	0.36	6.26	4.42	16.48	46.11	9.38	3.90	6.78	0.21	255.6	149.0	4.3	73.8
45	8.61	7.36	0.31	4.91	7.54	11.05	49.27	8.10	6.28	5.10	0.09	220.9	32.3	2.8	58.7
46	336.45	5.93	0.35	6.31	6.45	13.81	46.27	9.30	4.68	6.75	0.14	234.2	81.0	3.4	79.2
47	10.00	1.10	0.40	6.98	3.16	16.87	50.85	10.83	1.78	7.81	0.23	233.8	60.9	5.3	56.5
48	2.44	0.16	1.29	10.27	0.32	18.77	42.85	15.44	1.50	9.16	0.22	233.8	47.4	6.6	54.4
49	46.85	20.89	0.22	4.21	10.19	7.67	38.90	5.19	9.37	3.22	0.14	219.0	55.5	2.6	72.0
50	2.24	30.03	0.40	6.59	14.15	7.08	25.28	4.34	9.14	2.84	0.16	202.9	11.0	2.7	46.7
51	75.98	20.47	0.32	4.93	11.95	7.15	34.71	5.04	10.86	4.35	0.21	220.8	61.1	2.5	64.5
52	11.55	22.27	0.24	3.50	10.68	6.17	38.24	4.97	11.66	2.21	0.07	217.4	45.0	2.2	64.0
53	5.32	7.60	0.08	2.09	7.22	8.83	60.88	6.21	5.69	1.36	0.02	229.3	36.3	2.3	55.8
54	39.24	22.86	0.37	4.33	12.27	5.43	31.72	4.94	13.96	3.99	0.14	226.8	43.3	2.2	67.9

Tab. 1 cont.

1	2	Share of geomorphons										Morphometric parameters			
		3	4	5	6	7	8	9	10	11	12	13	14	15	16
55	20.98	0.78	0.72	8.46	1.30	21.17	45.97	11.17	1.13	8.93	0.38	252.4	81.0	5.2	73.6
56	50.57	1.66	0.69	9.18	2.00	20.46	45.07	10.78	1.22	8.37	0.57	244.1	108.8	5.8	72.1
57	8.43	0.30	0.11	4.85	1.14	16.43	64.75	7.05	0.38	4.58	0.41	228.2	74.6	5.1	61.8
58	9.56	0.97	0.62	8.55	0.82	20.41	51.80	8.83	0.35	7.10	0.55	227.8	93.6	6.4	59.2
59	29.95	1.29	0.59	10.42	1.62	23.21	44.11	9.19	0.88	7.50	1.19	241.6	103.9	7.1	71.8
60	30.74	2.03	0.74	8.59	2.38	18.62	47.61	9.81	2.15	7.28	0.78	232.2	85.6	5.1	67.8
61	19.14	0.68	0.84	10.27	0.87	22.63	44.30	10.69	1.18	7.77	0.78	234.6	92.2	6.5	78.9
62	28.76	1.74	0.55	7.48	2.53	18.73	49.80	10.49	1.97	5.96	0.76	242.4	91.5	5.0	70.8
63	164.60	0.32	0.68	9.10	0.79	21.83	45.34	11.21	0.84	9.37	0.52	246.0	121.9	5.9	73.2
64	611.38	3.18	0.54	8.21	3.31	17.97	45.23	10.41	2.77	8.09	0.30	233.2	129.8	4.5	74.5
65	59.71	29.03	0.42	5.33	10.96	6.80	28.32	4.87	9.66	4.28	0.34	199.6	47.0	2.6	68.0
66	0.61	6.71	1.73	10.98	8.48	14.55	38.45	7.52	4.04	6.49	1.05	188.1	15.9	4.2	68.1
67	3.18	25.05	0.67	6.64	12.45	6.53	29.83	3.97	9.94	4.37	0.54	186.6	19.1	2.7	54.5
68	3.10	32.17	0.57	5.80	13.49	5.65	25.00	3.47	9.63	3.85	0.36	187.6	14.3	2.7	52.8
69	6.52	0.01	1.28	14.70	0.03	24.83	35.65	11.46	0.20	9.73	2.09	278.8	104.2	9.1	59.4
70	25.77	48.70	0.37	4.33	9.47	3.99	19.04	2.55	8.95	2.45	0.15	174.4	26.3	2.3	71.2
71	3.57	27.83	0.63	6.17	13.41	5.34	25.55	3.50	14.01	3.51	0.04	170.2	14.9	2.2	61.4
72	0.76	28.25	0.46	8.24	11.57	8.46	27.48	3.06	9.97	2.48	0.03	174.5	16.7	3.0	50.2

1 – number of patch; 2 – area (km²); geomorphon types (3–12): 3 – flat, 4 – summit, 5 – ridge, 6 – shoulder, 7 – spur, 8 – slope, 9 – hollow, 10 – footslope, 11 – valley, 12 – depression; 13 – mean height (m a.s.l.); 14 – local relief (m); 15 – mean slope (degree); 16 – slope range (degree)

Table 2

Summary morphometric characteristics of the patches in each group

Parameter	Group			
	1	2	3	Total
Number of patches	24	36*	12	72
Sum area [km ²] [% of patches' area]	728.5 (21.52)	2,415.3 (71.37)	240.8 (7.11)	3,384.6 (100.0%)
Mean area	30.36	67.09	20.07	47.01
Min	0.15	0.61	0.76	0.15
Max	447.19	611.38	75.98	611.38
Mean height [m a.s.l.]	262.96	234.78	211.78	239.42
Min	123.46	121.69	156.70	121.69
Max	358.25	353.24	254.80	358.28
Mean local relief [m]	83.81	79.19	31.34	72.75
Min	46.53	15.95	10.96	10.96
Max	130.19	149.08	61.13	149.08
Mean slope [°]	7.60	4.80	2.89	5.24
Min	0.00	0.00	0.00	0.00
Max	80.44	79.91	72.03	80.44
Mean slope range [°]	66.40	69.33	59.39	66.69
Min	54.36	37.12	46.70	37.12
Max	80.43	79.91	72.03	80.43

* – maximum values in bold

ranging from 0.0 to 48.70%. Shoulder (3.64%) and footslope (3.19%) elements have area proportions of individual patches in the ranges of 0.0–14.15% (shoulder) and 0.0–14.01% (foot-slope). The lowest, and similar, proportions have geomorphons located in the lowest and highest positions – depression ele-

ments (0.58% of the area of the patches) and summit elements (0.55% of the area of the patches); their ranges of values in individual lobes are also similar (0.02–2.95% and 0.01–2.58%, respectively).

Three groups of lobes were distinguished, having their own unique characteristics expressed in terms of the different proportion of area and spatial distribution of geomorphons, as well as of the values of individual morphometric parameters (Figs. 5–7). Within the patches belonging to each group, internal differentiation and the existence of subgroups of lower rank are clear (Fig. 3).

Twenty-four patches were included in group 1. In this group some differences in relief can be observed (Fig. 6: 1_1–1_6) expressed by the pattern of geomorphons. This group includes patches having the largest areas on Western Roztocze and the Grabowiec Interfluvium (Fig. 2). Smaller patches from this group occur on the Nałęczów Plateau (SW part), Western Roztocze (SE part), in the neighbourhood of the Wieprz River Valley on Middle Roztocze, and one patch each on Eastern Roztocze, the Sokal Ridge and the Gielczew Hills. In total, the patches belonging to this group cover 728.5 km² (21.52% of the area of all patches). Compared to the other groups, the patches belonging to group 1 are distinguished by the highest average elevation (246.94 m a.s.l.) and the highest average slope (5.53°; Figs. 5A, C and 7). In terms of the proportion of area of each geomorphon type (Table 3 and Fig. 4), the lowest are flat; shoulder and footslopes, and the highest are summit, ridge, hollow, valley and depression. Based on this, it can be concluded that the relief of these patches is characterized by great variety. There are almost no flat surfaces here, and summits are clearly marked by gentle ridges and their culminations. There are deeply incised broad valleys and depressions, and slopes are strongly dissected by smaller valleys. Taking into account the values of correlation statistics in this group (Table 4) and the structure of the dendrogram and heat map (Fig. 3A, B), it can be concluded that

Table 3

Summary share of geomorphons in the area of patches [%] of each group

Geomorphon type	Value	Group			
		1	2	3	Total
Flat	Mean	0.15	4.58	26.00	6.67
	Min	0.00	0.78	13.36	0.00
	Max	0.68	22.86	48.70	48.70
Summit	Mean	0.83	0.56	0.44	0.63
	Min	0.01	0.08	0.18	0.01
	Max	2.58	1.73	0.83	2.58
Ridge	Mean	13.91	8.14	5.74	9.66
	Min	4.85	2.09	3.23	2.09
	Max	22.73	12.40	9.89	22.73
Shoulder	Mean	0.43	4.34	11.31	4.19
	Min	0.00	0.82	8.05	0.00
	Max	1.60	12.27	14.15	14.15
Spur	Mean	25.61	17.09	7.01	18.25
	Min	10.74	5.43	3.99	3.99
	Max	36.42	24.13	11.58	36.42
Slope	Mean	39.79	46.02	31.03	41.44
	Min	26.76	31.72	19.04	19.04
	Max	64.75	65.48	49.20	65.48
Hollow	Mean	9.80	8.65	4.38	8.43
	Min	5.58	3.57	2.55	2.55
	Max	15.84	12.08	5.92	15.84
Footslope	Mean	0.54	3.37	10.20	3.56
	Min	0.00	0.35	7.77	0.00
	Max	1.97	13.96	14.01	14.01
Valley	Mean	7.78	6.68	3.68	6.55
	Min	3.60	1.05	2.20	1.05
	Max	12.43	11.01	7.33	12.43
Depression	Mean	1.16	0.59	0.20	0.72
	Min	0.03	0.02	0.03	0.02
	Max	2.95	1.45	0.54	2.95

* – maximum values in bold

the patches in this group are characterized by a moderate degree of similarity, placing them between groups 2 and 3.

Group 2 includes 36 patches, covering a total of 2,415.3 km², which is 71.37% of the total area of loess patches in the study region. The patches in this group are the largest, with an average area of 67.09 km², the largest reaching 611.38 km². They occupy almost all of the Sokal Ridge and the Urzędów Heights, a significant part of the Nałęczów Plateau and Grabowiec Interfluve, and form several areas in the SE part of the Gielczew Hills. This group is distinguished from the first by a significantly smaller proportion of summits and ridges (Fig. 6: 2_1–2_6). Although, there are areas (Fig. 6: 2_1) where relief locally is similar to that of group 1. These patches are distinguished by the highest mean local relief (Table 1 and Fig. 7) and the highest proportion of slope geomorphon surfaces (Table 3 and Fig. 4). The proportion of flat type geomorphon is higher here than in group 1. The share of the area of each type of geomorphon allows us to conclude that the relief of the patches in this group is less varied than within the patches of group 1 (Table 3 and Fig. 4). On the tops, there are smaller proportions of ridge and culmination surfaces, a larger proportion of flat surfaces, and the slopes are longer and more gently sloping. The patches in this group have the lowest average correlation value in the group, which indicates that they are very differ-

entiated, as also reflected by the highest standard deviation (Table 4).

Group 3 includes 12 patches with a total area of 240.8 km² which is 7.11% of the area of all patches in the study region. They are located in the Hrubieszów Basin, Zamość Basin, Świdnik Plateau and on the outskirts of the Nałęczów Plateau, Bełżyce Plateau, S part of the Gielczew Hills and inside the Sokal Ridge. These are the patches with the smallest average area (20.07 km²), the smallest average elevation of 211.78 m a.s.l. and the smallest local relief (31.34 m). The average slope (2.89°) is also the lowest here (Table 2 and Fig. 7). This group is distinguished by the highest proportion of flat (average 26.00%), shoulder (11.31%) and footslope (10.20%) geomorphons (Table 3 and Fig. 4). Within some patches, the proportion of flat and slope geomorphons reaches 22.48 and 65.48%, respectively. Thus, the surface shape of individual patches in this group varies greatly (Fig. 6: 3_1–3_5), but they tend to be quite flat and less dissected. This group is the lowest internally differentiated (Fig. 3A, B), as shown by the highest mean, minimum and median correlation values in the set, and the lowest standard deviation (Table 4).

DISCUSSION

The relief of individual loess patches in Poland is strongly differentiated, due to local conditions of loess accumulation in the Pleistocene (including the relief of the sub-loessic subsoil) and the course of postglacial natural and anthropogenic morphogenetic processes (Maruszczak, 1954, 1958, 1961; Kęsik, 1961; Harasimiuk and Henkiel, 1976, 1978a; Kida, 1996; Rodzik et al., 1998; Kołodyńska-Gawrysiak and Poesen, 2017; Kołodyńska-Gawrysiak et al., 2018). Previous studies of loess cover relief in Poland have primarily aimed at understanding the genesis and evolution of individual loess relief forms such as seminatural and anthropogenic gullies (Schmitt et al., 2006; Dotterweich et al., 2012; Superson et al., 2014) and closed depressions (Maruszczak, 1958; Kołodyńska-Gawrysiak and Poesen, 2017; Kołodyńska-Gawrysiak et al., 2019), as well as the rates of relief change due to soil erosion (Zglobicki, 2002; Rodzik et al., 2005; Rejman and Rafalska-Przysucha, 2015). The density of gully networks has also been studied using analogue methods, based on topographic data (Buraczyński, 1975, 1977; Maruszczak, 1973; Jary, 1991; Józefaciuk and Józefaciuk, 1992; Jary and Kida, 2002) and digital data (Dobek et al., 2011; Gawrysiak and Harasimiuk, 2012).

The use of geomorphometric methods, based on high-resolution elevation data (DTM), provides new opportunities, allowing precise quantitative analysis of the relief of loess covers, allowing the comparison of features between different loess covers, and making it possible to assess their specificity (Jasiewicz and Stepinski, 2013; Gawrysiak, 2019; Du et al., 2019; Ding et al., 2021). This will facilitate the understanding of local conditions affecting the accumulation and morphology of loess covers (Harasimiuk and Henkiel, 1976, 1978a; Dolecki, 1978; Kołodyńska-Gawrysiak, 2019b). Thanks to the use of DTMs and their derivatives, including geomorphons-geomorphometric features – the classification of loess covers of the study area was made based on morphometric parameters, distinguishing 3 groups of covers with common relief features. This is a different, geomorphometrics-based approach from previous quantitative relief analyses of loess patches (Fang et al., 2008; Hu et al., 2020; Wei et al., 2021).

Analysis of the areal proportions of each geomorphon type within the loess patches distinguished in the study area, com-

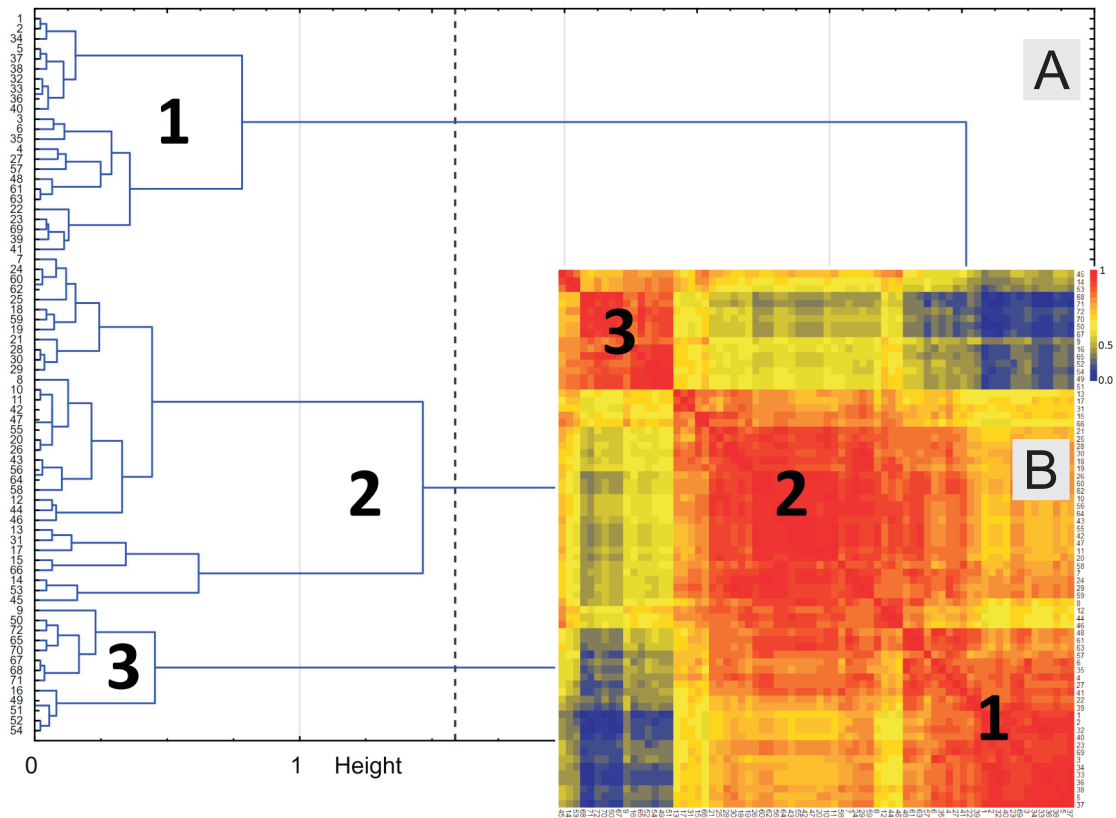


Fig. 3. Dendrogram (A) and heat map (B) illustrating the formation of similarity between loess patches based on the distribution of morphometric parameter values and the proportion of geomorphon area (numbers on the left side of the diagram and on the edges of the heat map indicate individual patches, according to Figure 1; large numbers 1, 2 and 3 indicate groups of patches)

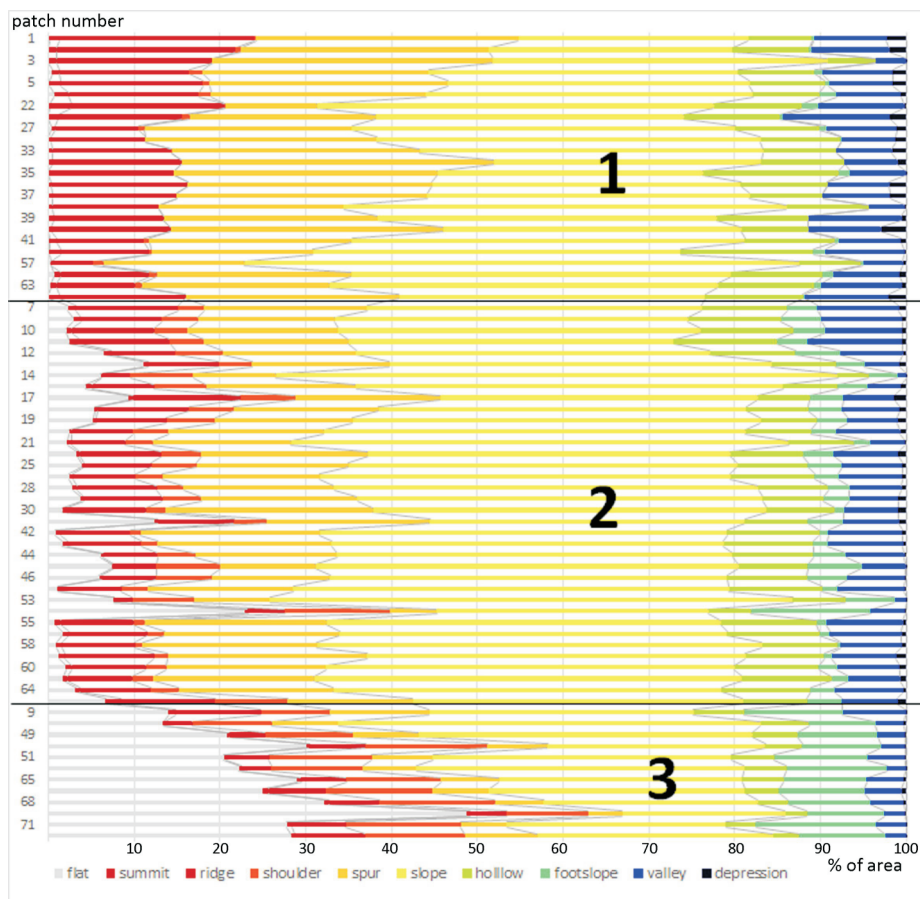


Fig. 4. Share of geomorphon areas by patch groups

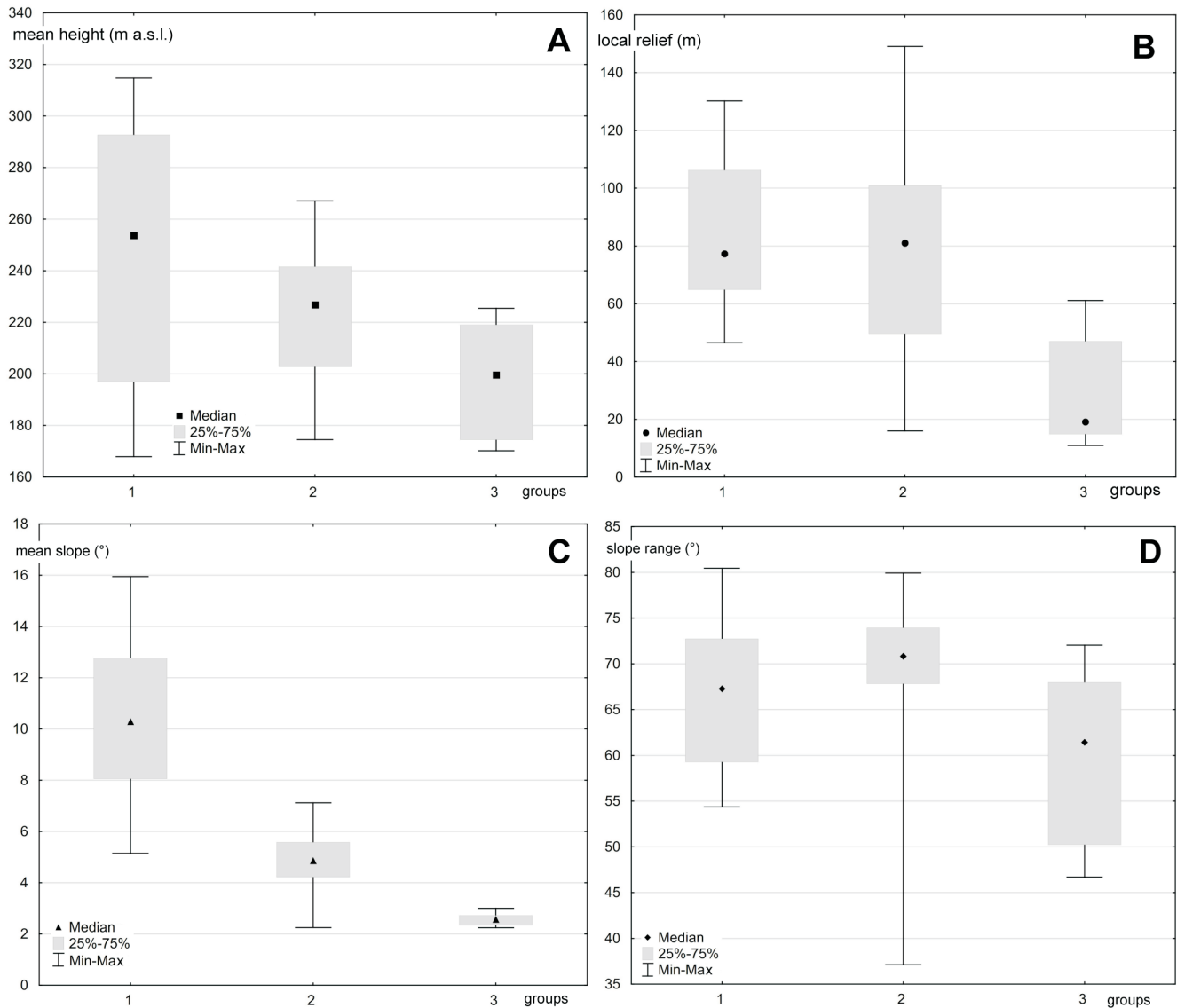


Fig. 5. Variation of mean height (A), local relief (B), mean slope (C) and slope range (D) values by patch groups

combined with morphometric parameters, allowed quantitative characterization of their relief. It was found that each of the patches has unique characteristics expressed by these parameters. Using hierarchical clustering, they were combined into groups characterized by a certain degree of similarity, expressed by Kendall's tau correlation index. Thus, large proportions of the area of summit, ridge, hollow, valley and depression geomorphons, combined with high local relief and high slopes, are characteristic of patches with high relief dynamics (Figs. 4–7), included in group 1. Here, flatness is almost completely absent, the proportions of the slope geomorphon are lower than in the other groups, and the dissection of slopes expressed by higher proportions of hollow is marked. The second type of relief (group 2) is represented by patches within which flat surfaces appear, slope geomorphon proportions are higher and average slopes are lower. Nevertheless, this group is quite similar to group 1. The third group includes patches with the least relief diversity, which is reflected in the lowest absolute and local relief, and the lowest average slopes, which are usually accompanied by a high proportion of flat surfaces. At the same time, this

group is characterized by the greatest internal differentiation (Table 3).

The three groups of loess patches distinguished show some patterns in distribution. The patches of group 1 are located in areas with the highest absolute heights of the sub-loess topography. These are the high-elevation areas of the Lublin Upland, such as Western Roztocze, the southwestern part of the Grabowiec Interfluvium and the Nałęczów Plateau, together with the structurally-based marginal zones of both regions. There is also usually high local relief. Significant land slopes and an elevated proportion of geomorphons defining culminations and the bottoms of depressions (summit, ridge, spur, hollow, valley and depression) in the inner parts of the patches are characteristic of these patches. This makes their relief varied. By contrast, group 3 patches are usually located in lower-lying parts of the region such as the Zamość Basin and Hrubieszów Basin. They are characterized by the lowest local relief and slopes and the highest proportion of flat, shoulder and footslope geomorphons, which define flat or weakly sloping surfaces. Group 2, which occupies more than 71% of the loess cover area, includes pat-

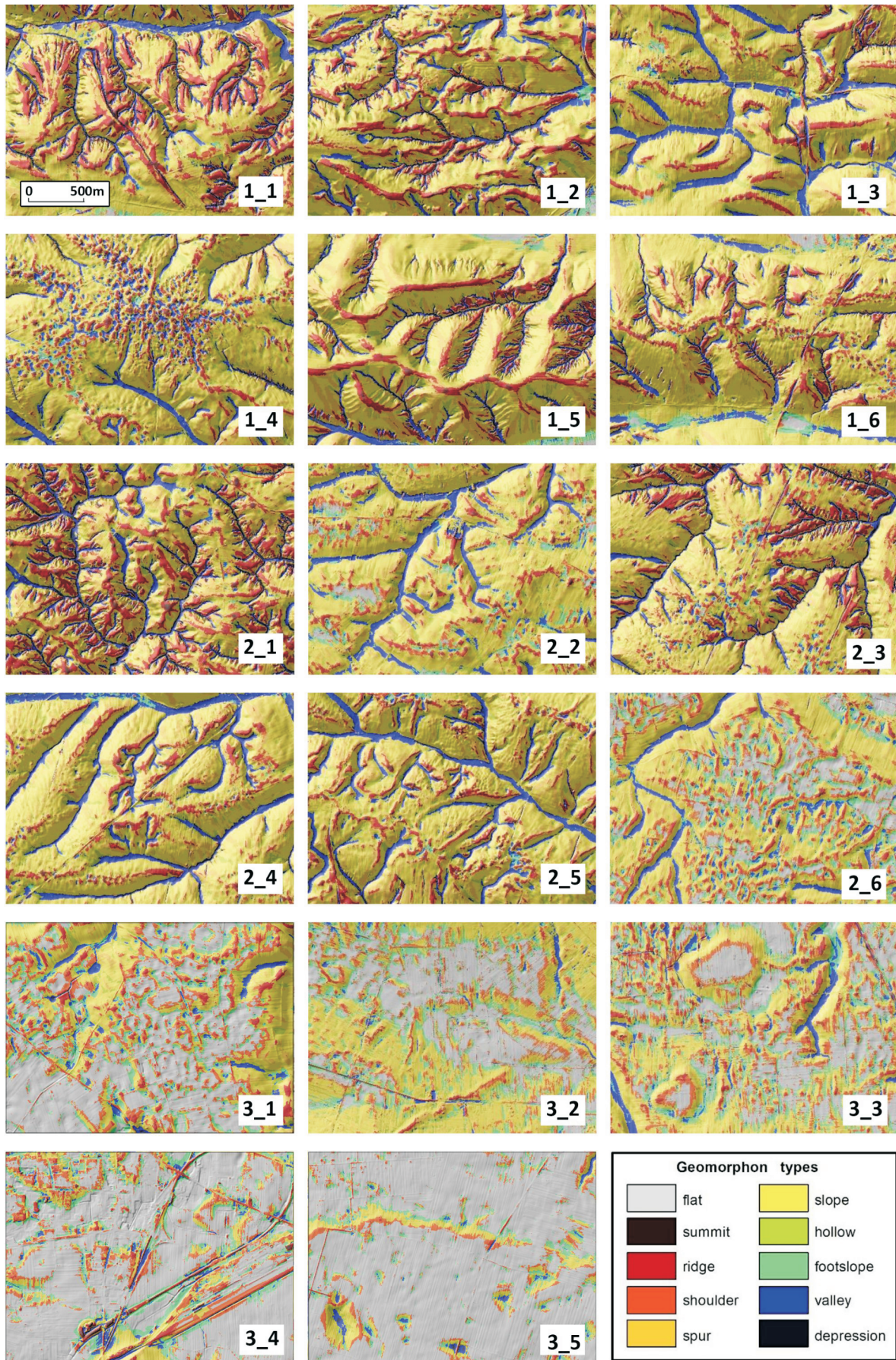


Fig. 6. Example maps of geomorphons representing the relief types of the 3 groups of patches distinguished

Location in [Figure 2](#)

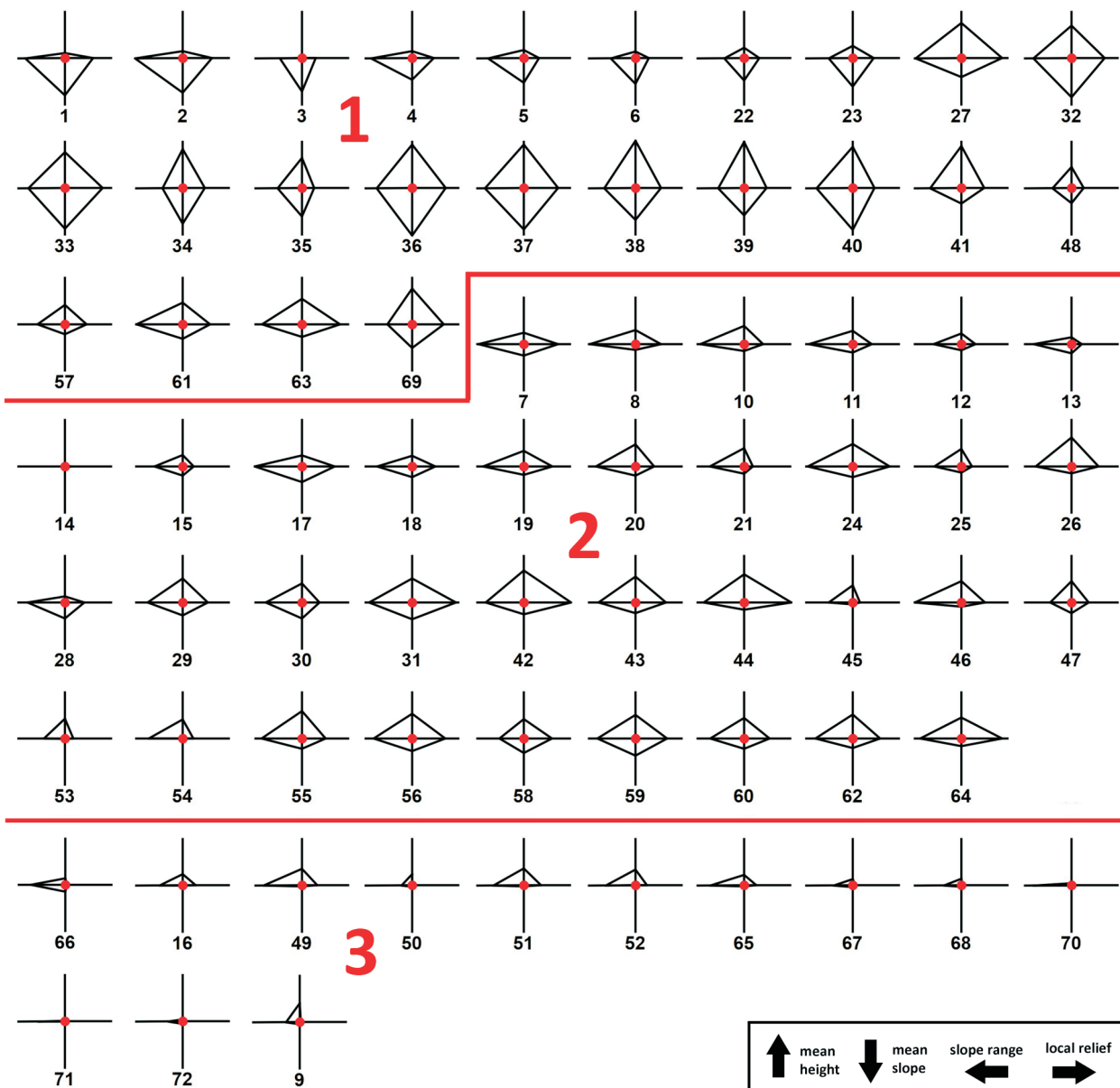


Fig. 7. Variation of mean height, local relief, mean slope and slope range values in individual patches, arranged by groups

The distance from the centre of the array (red dot) to the apex of the polygon represents the spread of a given variable in relation to the range of values in the entire set

ches with intermediate features. The largest share of these is the slope geomorphon. These covers have the highest average and maximum local relief. This group is the most similar internally, as reflected by the highest average correlation between patches. This group includes the extensive loess covers of the Nałęczów Plateau, the Sokal and Horodło ridges and the Grabowiec Interfluve, as well as several smaller ones.

The proportion of geomorphons of each type and their distribution in separate groups can be influenced by the morphology of the sub-loess surface, as well as the thickness of the loess cover. This relationship is clearly legible in the case of loess patches belonging to the first group, which includes the area of Szczepieszyn Roztocze and the southwestern part of the Nałęczów Plateau. In these areas, the influence of primary sub-loess relief, often conditioned by the structure of the bed-

rock, on the formation of the loess cover is particularly pronounced (Harasimiuk and Henkiel, 1976, 1978a; Wagrowski, 1996; Schmitt et al., 2006). With the thickness of the loess cover not exceeding ~10 m, there is a dense network of deeply incised erosion-denudation valleys in the bedrock, the presence of which influences the relief of the sub-loess surface exceeding 100 m (Maruszczak et al., 1984; Pożaryski et al., 1994; Gardziel et al., 2006). As a result, these areas are distinguished by high local relief, which influenced the largest proportion of geomorphons such as summit, ridge, hollow, valley and depression, defining convex and concave areas. In addition, the patches in this group are characterized by a moderate degree of similarity in the spatial pattern of geomorphons, which may be due to the local conditions of the loess cover, related to sub-loess relief. The patches of group two cover the largest

Table 4

Basic statistics of Kendall Tau correlation matrix of loess patches

Parameter	Group 1	Group 2	Group 3	Total
Mean	0.8709	0.8296	0.8944	0.7123
Min	0.7143	0.5385	0.8022	0.2527
Max	1.0000	1.0000	1.0000	1.0000
Standard deviation	0.0584	0.1102	0.0490	0.1768
Median	0.8681	0.8681	0.8890	0.7582

* – bolded maximum values

area in the region and are characterized by the greatest variation in relief. It is possible to find areas with morphology very similar to that of group 1, but areas with slightly different morphometric features and spatial arrangement of geomorphons predominate. Probably, where the local relief and slopes are higher there is a greater proportion of extreme geomorphons (ridges, summits vs. valleys and depressions), and where the lower relief is more gentle, it is manifested by higher proportions of the slope geomorphon. The third group included patches with very similar morphological positions. These are the bottoms of extensive depressions (Zamość Basin, Hrubieszów Basin), the surface of a low plateau (Świdnik Plateau) and the lower section of the Por Valley (Giełczew Hills outer zone). Everywhere there, the relatively thin loess cover lies on poorly resistant marls (Zamość Basin; Buła et al., 1994), loose Quaternary deposits building up the over-flood terraces (lower Huczwa River; Dolecki, 1978, 1999; Rzechowski et al., 2009) or directly on chalk, silts and sands near Łęczna (Harasimiuk and Henkiel, 1978b, 1981). The low loess thickness and the little-varied relief and lithological features of the sub-loessic surface do not predispose the formation of more significant local denudation and, consequently, features of "living" loess relief. This is reflected in the low values of morphometric indices (Fig. 7) and the significant proportion of the flat geomorphon (Table 2).

Quantitative morphological analysis was carried out for entire areas of the loess cover, which may lead to generalization of the results. This is especially true for large loess patches with internally varying morphology. Thanks to this approach the Szczepieszyn area (patch no. 31 in Western Roztocze – the eastern part called "Szczepieszyn Roztocze") was classified

into group 2 characterized by the lower relief dynamics. This cover is locally characterized by "vivid" relief (Buraczyński, 1989), corroborated by high values of DTM derivatives, but the morphology of its other parts, especially the high proportion of flats (Fig. 4) led to its classification into group 2. Another example is the extensive cover number 7, covering the western part of the Nałęczów Plateau. In terms of morphological features (Fig. 6: 2_1), this cover is very similar to map 1_1, but lower values of morphometric parameters (Fig. 7) and a higher proportion of the flat geomorphon (Fig. 4) place it in group 2.

In order to study the internal structure of loess patches' relief, it is necessary to use an approach in which patches are divided into smaller areas (tiles) and in them morphometric characteristics are calculated, and then combined into groups on the basis of similarity. In this way, it will probably be possible to internally differentiate large patches and properly classify their parts. This is the subject of a separate study (Gawrysiak and Kociuba, 2023).

CONCLUSIONS

The study used a new approach to analysing the morphology of loess patches, based on geomorphometric analyses performed on the basis of a Digital Terrain Model and its selected derivatives. It allowed quantitative relief analysis and clustering of patches based on the similarity of the morphometric parameters studied. There were 3 groups of patches with similar relief characteristics expressed by a similar range of morphometric parameters. The quantitative results of this relief analysis of the loess patches facilitate the understanding of local conditions affecting the accumulation and morphology of loess covers.

These analyses and their results do not exhaust the subject, which is the morphological differentiation of loess covers. The next step should be to isolate and study the factors that conditioned the separate development of the loess patches' relief, and which consequently led to such differentiation of this relief.

Acknowledgements. We would like to thank geomorphologists from the Faculty of Earth Sciences and Spatial Management of Maria Curie-Skłodowska University in Lublin who discussed and helped to clarify the boundaries of loess covers on the Lublin Upland. Special thanks go to the volume editors and the anonymous reviewers for valuable advice and useful comments on the manuscript.

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