Geological Quarterly, 2023, 67: 53
DOI: http://dx.doi.org/10.7306/gq.1723

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

Leszek GAWRYSIAK[1] and Renata KOŁODYŃSKA-GAWRYSIAK[1]

[1] Maria Curie-Skłodowska University, Faculty of Earth Science and Spatial Management, Al. Kraśnicka 2 CD, 20-718 Lublin, Poland; ORCID: 0000-0002-6580-5067 [L.G.], 0000-0003-0360-7556 [R.K-G.]

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; Lehmkuhl et al., 2021), of some European regions (Lindner et al., 2017; Lehmkuhl 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-

* Corresponding author, e-mail: leszek.gawrysiak@mail.umcs.pl,
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-

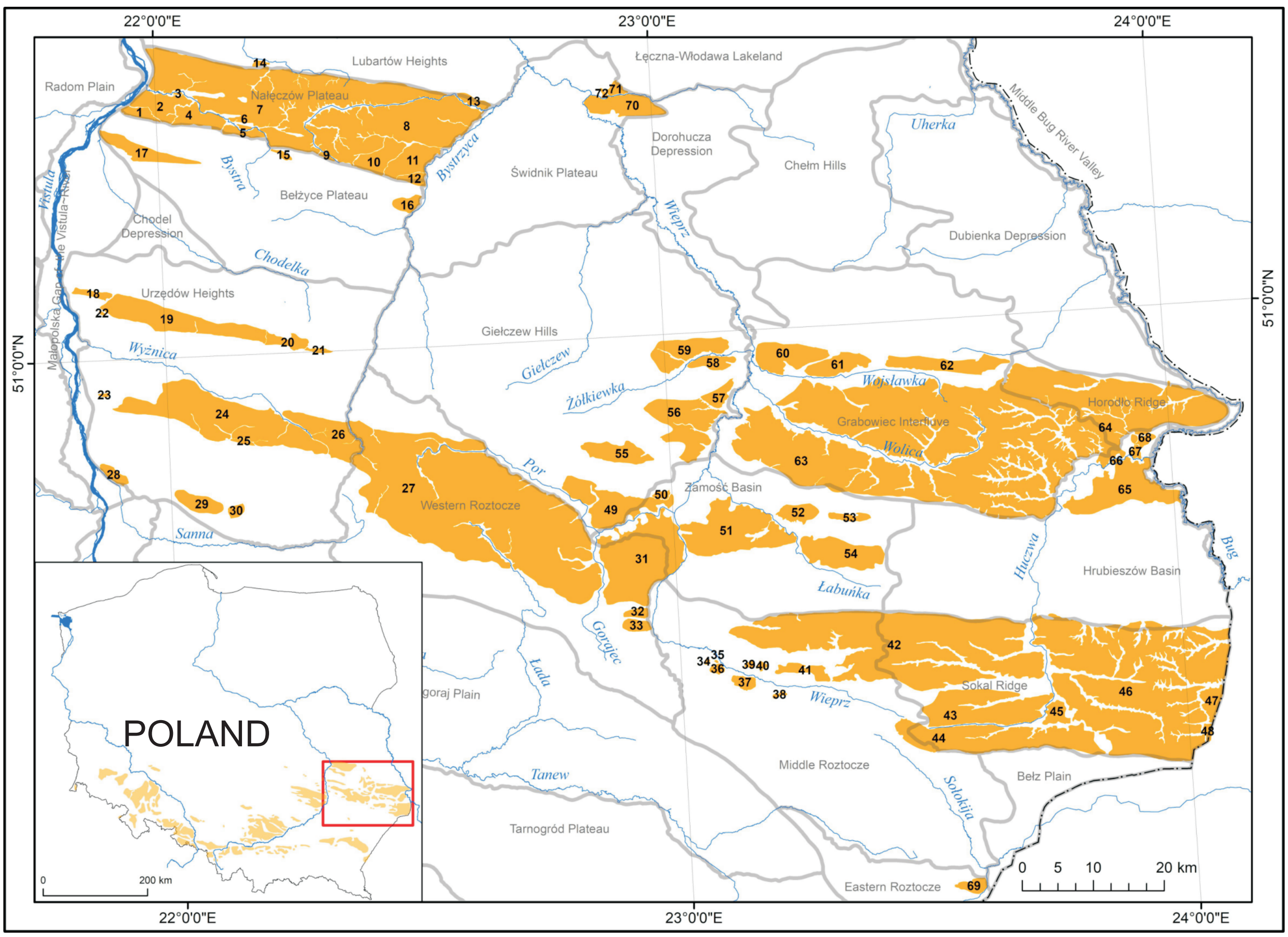


**Fig. 1. Distribution of loess patches (numbered from 1–72) against the background of mesoregion boundaries (after Gawrysiak and Kociuba, 2023, modified and completed) according to the physical geographical divisions of Solon (2018)**

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 km$^2$ 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 almost entire mesoregions (Fig. 1). In the study area, 72 loess patches were mapped (Fig. 1–4). The average size of a patch is 47 km$^2$, though the largest (Grabowiec Interfluve – Horodło Ridge) reaches 611.4 km$^2$ (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

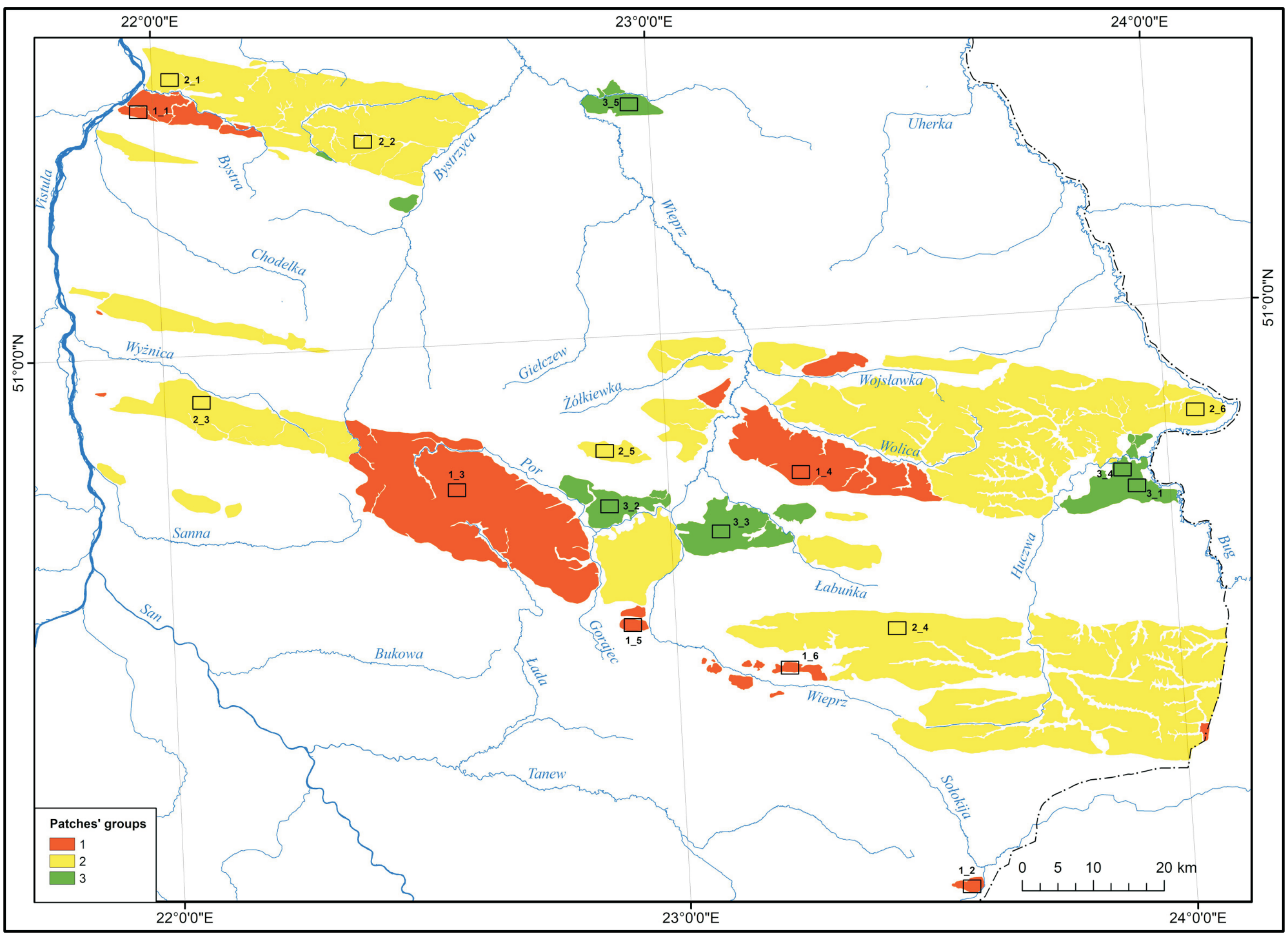


**Fig. 2. Loess patches classified into groups on the basis of geomorphon proportions and selected morphometric features**

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 (km$^2$); 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$^2$]<br>[% of patches' area] | 728.5<br>(21.52) | **2,415.3**<br>**(71.37)** | 240.8<br>(7.11) | 3,384.6<br>(100.0%) |
| Mean area<br>Min<br>Max | 30.36<br>0.15<br>447.19 | **67.09**<br>0.61<br>611.38 | 20.07<br>0.76<br>75.98 | 47.01<br>0.15<br>611.38 |
| Mean height [m a.s.l.]<br>Min<br>Max | **262.96**<br>123.46<br>358.25 | 234.78<br>121.69<br>353.24 | 211.78<br>156.70<br>254.80 | 239.42<br>121.69<br>358.28 |
| Mean local relief [m]<br>Min<br>Max | **83.81**<br>46.53<br>130.19 | 79.19<br>15.95<br>149.08 | 31.34<br>10.96<br>61.13 | 72.75<br>10.96<br>149.08 |
| Mean slope [°]<br>Min<br>Max | **7.60**<br>0.00<br>80.44 | 4.80<br>0.00<br>79.91 | 2.89<br>0.00<br>72.03 | 5.24<br>0.00<br>80.44 |
| Mean slope range [°]<br>Min<br>Max | 66.40<br>54.36<br>80.43 | **69.33**<br>37.12<br>79.91 | 59.39<br>46.70<br>72.03 | 66.69<br>37.12<br>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% (footslope). The lowest, and similar, proportions have geomorphons located in the lowest and highest positions – depression elements (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 Interfluve (Fig. 2). Smaller patches from this group occur on the Nałęczow 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 Giełczew Hills. In total, the patches belonging to this group cover 728.5 km$^2$ (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 | Group 2 | Group 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 km$^2$, 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 km$^2$, the largest reaching 611.38 km$^2$. 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 Giełczew 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 differentiated, as also reflected by the highest standard deviation (Table 4).

Group 3 includes 12 patches with a total area of 240.8 km$^2$ which is 7.11% of the area of all patches in the study region. They are located in the Hrubieszow Basin, Zamość Basin, Świdnik Plateau and on the outskirts of the Nałęczów Plateau, Bełżyce Plateau, S part of the Giełczew Hills and inside the Sokal Ridge. These are the patches with the smallest average area (20.07 km$^2$), 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 (Zgłobicki, 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-

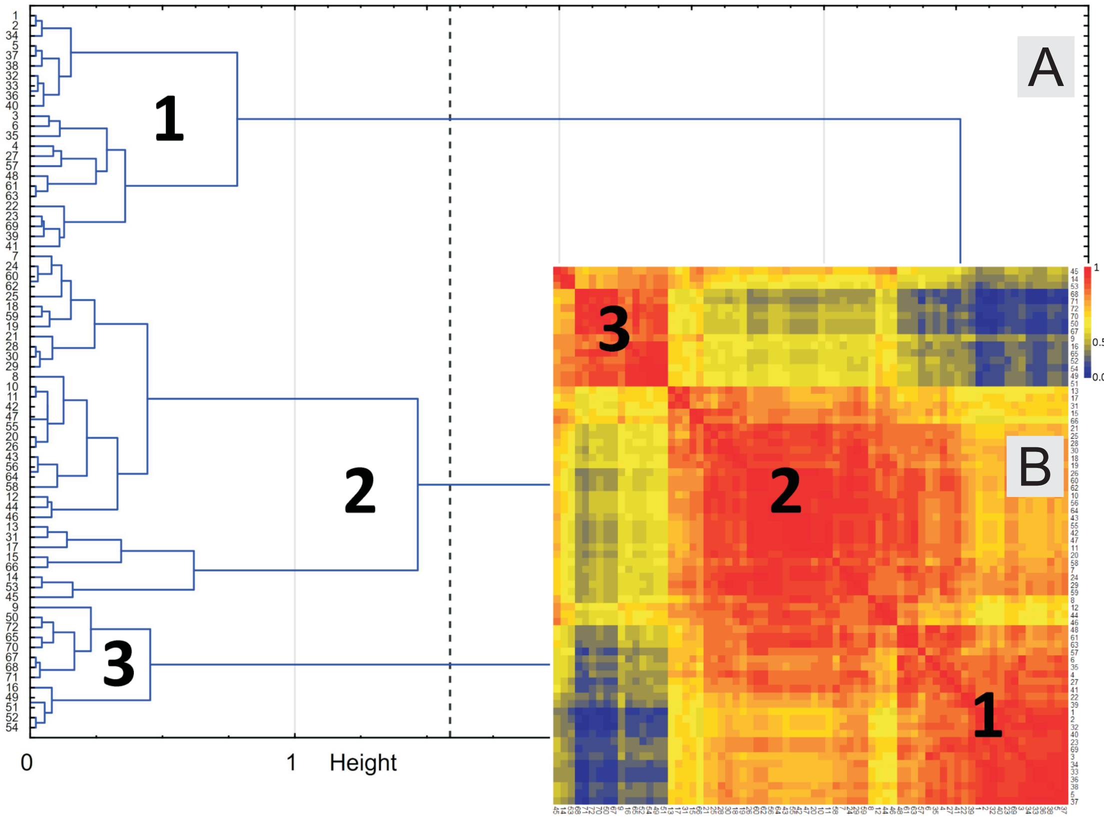


**Fig. 3. Dendrogram (A) and heat map (B) illustrating the formation of similarity between loess patches based on the distribution of morphometric parameter values and the proportion of geomorphon area (numbers on the left side of the diagram and on the edges of the heat map indicate individual patches,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

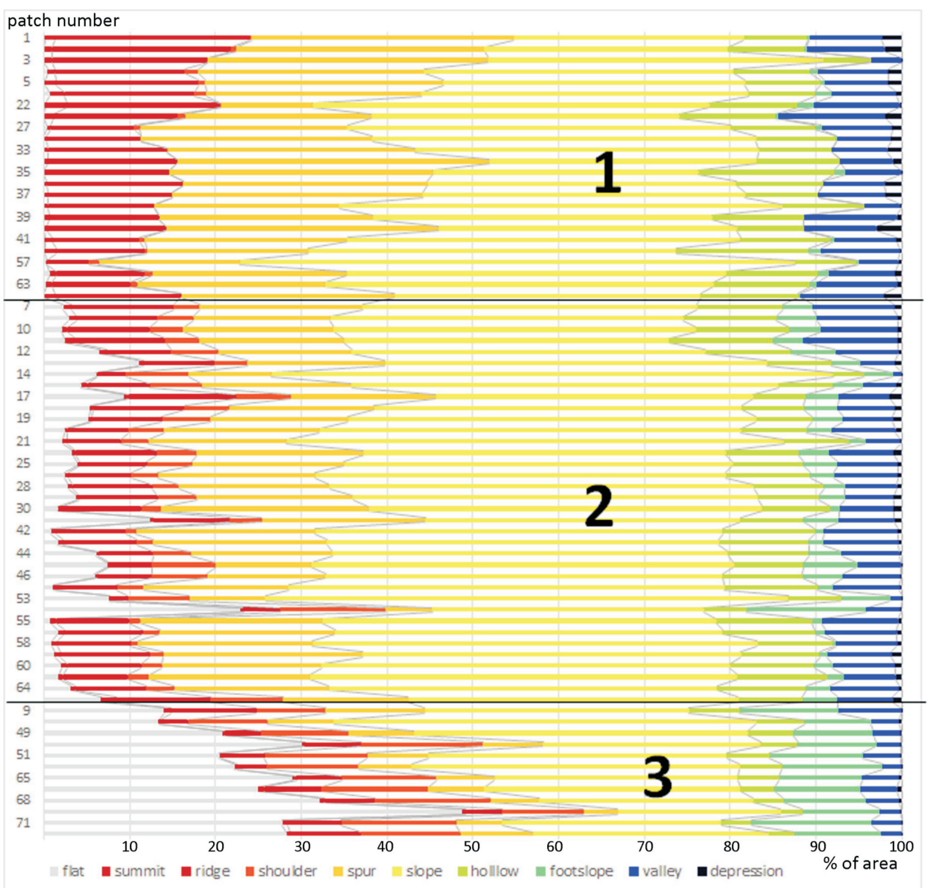


**Fig. 4. Share of geomorphon areas by patch groups**

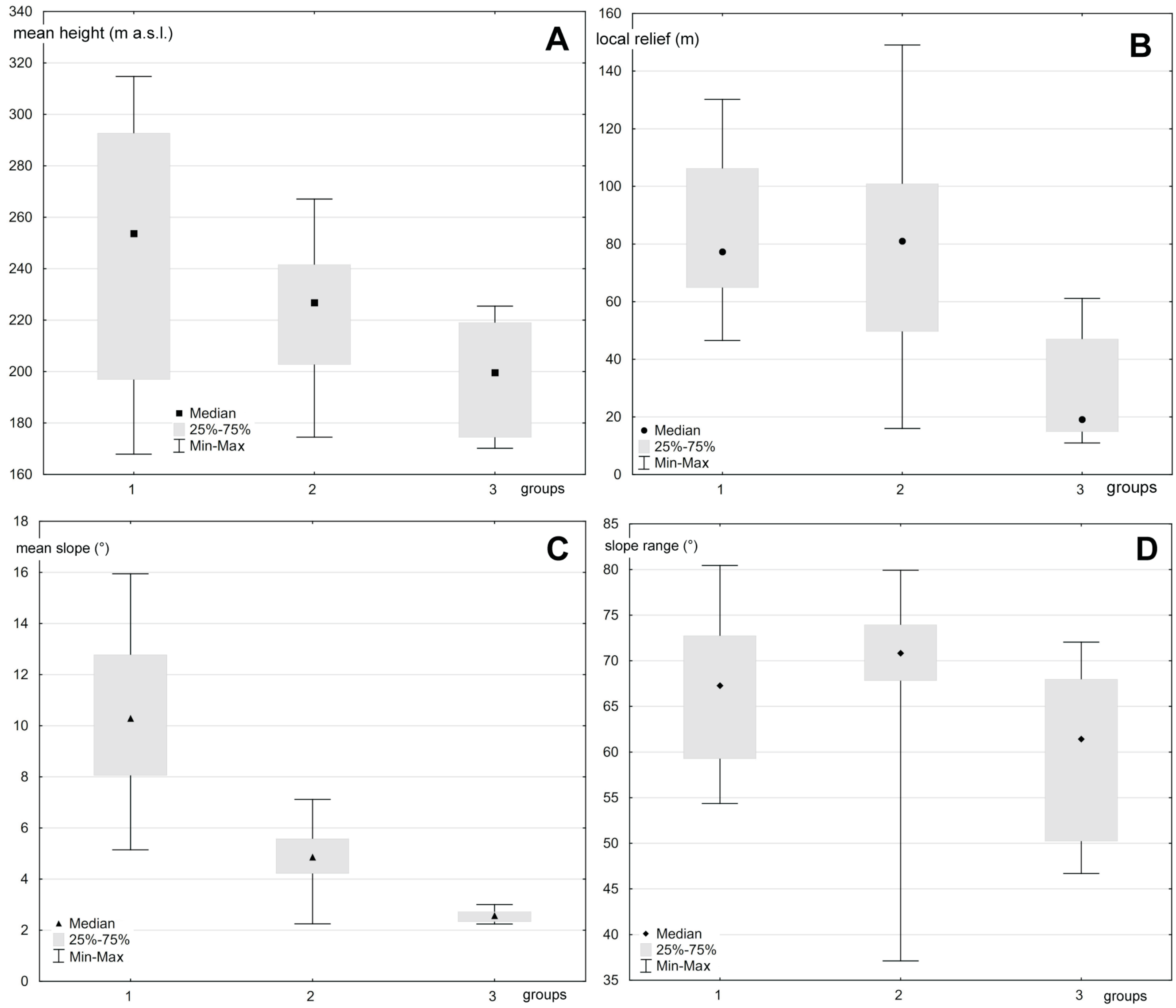


**Fig. 5. Variation of mean height (A), local relief (B), mean slope (C) and slope range (D) values by patch groups**

bined 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 Interfluve 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-

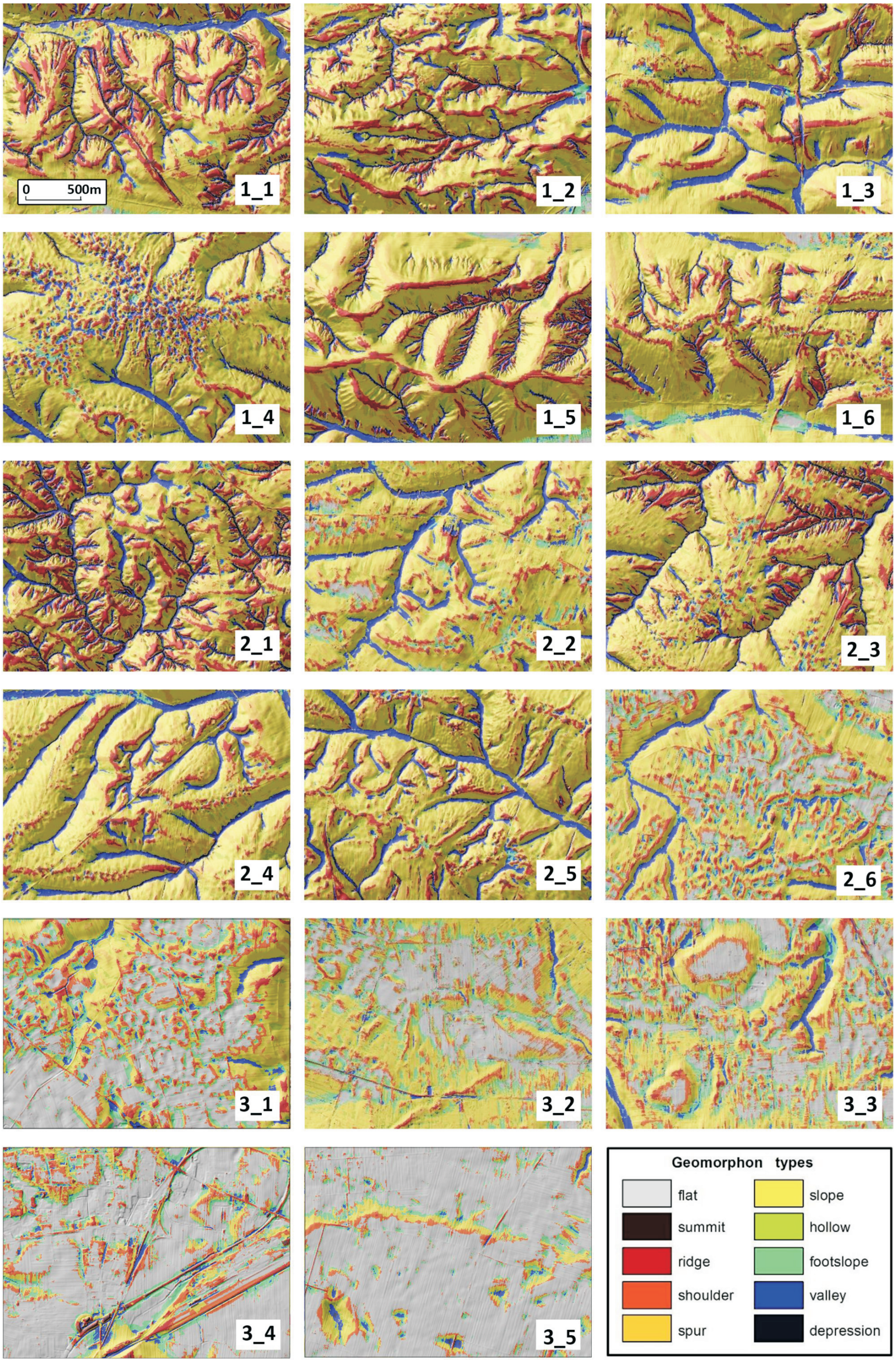


**Fig. 6. Example maps of geomorphons representing the relief types of the 3 groups of patches distinguished**

Location in Figure 2

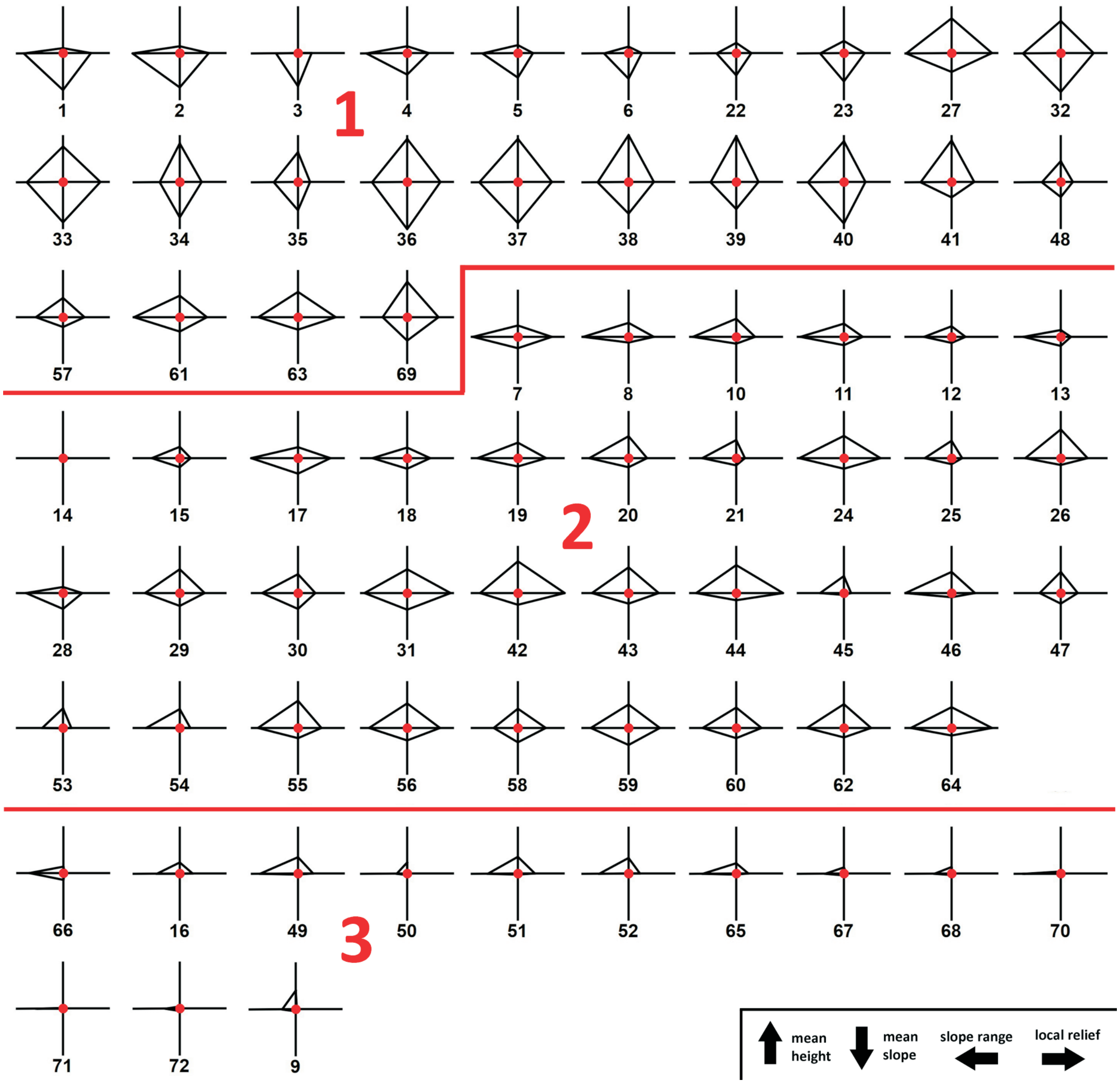


**Fig. 7. Variation of mean height, local relief, mean slope and slope range values in individual patches, arranged by groups**

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 Szczebrzeszyn Roztocze and the southwestern part of the Nałeczów Plateau. In these areas, the influence of primary sub-loess relief, often conditioned by the structure of the bedrock, on the formation of the loess cover is particularly pronounced (Harasimiuk and Henkiel, 1976, 1978a; Wągrowski, 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 Szczebrzeszyn area (patch no. 31 in Western Roztocze – the eastern part called "Szczebrzeszyn 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.

## REFERENCES

**Buła, S., Drzymała, J., Małek, M., 1994.** Szczegółowa Mapa geologiczna Polski w skali 1:50 000, ark. Nielisz – 0861 (in Polish). NAG, Państwowy Instytut Geologiczny – PIB, Warszawa.

**Buraczyński, J., 1975**. Gully erosion in Roztocze (in Polish with English summary). Folia Societatis Scientiarum Lublinensis, **17**: 13–19.

**Buraczyński, J., 1977.** Intensity of gully erosion and soil erosion in Roztocze Gorajskie (in Polish with English summary). Zeszyty Problemowe Postępów Nauk Rolniczych, **193**: 91–99.

**Buraczyński, J., 1989**. Development of the gullies in the Goraj Roztocze during the Last Millenium (in Polish with English summary). Annales UMCS, sec. B, (44–45): 95–104.

**Cao, M., Tang, G.A., Zhang, F., Yang, J., 2013.** A cellular automata model for simulating the evolution of positive–negative terrains in a small loess watershed. International Journal of Geographical Information Science, **27**: 1349–1363. https://doi.org/10.1080/13658816.2012.756882

**Ding, H., Na, J., Jiang, S., Zhu, J., Liu, K., Fu, Y., Li, F., 2021.** Evaluation of three different machine learning methods for object-based artificial terrace mapping – a case study of the Loess Plateau, China. Remote Sensing, **13**: 1021. https://doi.org/10.3390/rs13051021

**Dobek, K., Demczuk, P., Rodzik, J., Hołub, B., 2011.** Types of gullies and conditions of their development in silvicultural loess catchment (Szczebrzeszyn Roztocze region, SE Poland). Landform Analysis, **17**: 39–42.

**Dolecki, L., 1978.** A chart of the extent and depth of loesses in Grzęda Horodelska (in Polish with English summary). Folia Societatis Scientiarum Lublinensis, **20**: 26–29.

**Dolecki, L., 1999.** Sediments of the Pleistocene terraces of the Bug and Huczwa Rivers in the vicinity of Hrubieszow. Geological Quaterly **43** (1): 27–38.

**Dolecki, L., 2010**. Stratigraphy and main lithological features of loess formations in the south-eastern part of the Lublin Upland (SE Poland). Annales UMCS, sec. B, **55**: 7–42. https://doi.org/10.2478/v10066-010-0018-0

**Dolecki, L., Kołodziej, T., Mroczek, P., 2004**. Distribution of loess in the Lublin Upland and Roztocze, main study sites and actual research data (in Polish with English summary). Annales UMCS, sec. B., **59**: 9–35.

**Dotterweich, M., Rodzik, J., Zgłobicki, W., Schmitt, A., Schmidtchen, G., Bork, H.-R., 2012**. High resolution gully erosion and sedimentation processes, and land use changes since the Bronze Age and future trajectories in the Kazimierz Dolny area (Nałęczów Plateau, SE-Poland). Catena, **95**: 50–62. https://doi.org/10.1016/j.catena.2012.03.001

**Du, L., You, X., Li, K., Meng, L., Cheng, G., Xiong, L., Wang, G., 2019.** Multi-modal deep learning for landform recognition. ISPRS Journal of Photogrammetry and Remote Sensing, **158**: 63–75. https://doi.org/10.1016/j.isprsjprs.2019.09.018

**Fang, H., Cai, Q., Chen, H., Li, Q., 2008.** Effect of rainfall regime and slope on runoff in a gullied loess region on the Loess Plateau in China. Environmental Management, **42**: 402–411. https://doi.org/10.1007/s00267-008-9122-6

**Feng, L., Lin, H., Zhang, M., Guo, L., Jin, Z., Liu, X., 2020**. Development and evolution of Loess vertical joints on the Chinese Loess Plateau at different spatiotemporal scales. Engineering Geology, **265**: 105372. https://doi.org/10.1016/j.enggeo.2019.105372

**Gardziel, Z., Rodzik, J., 2005.** Rozwój wąwozów lessowych podczas wiosennych roztopów na tle układu pól (na przykładzie Kazimierza Dolnego) (in Polish). VII Zjazd Geomorfologów Polskich, Kraków: 125–132.

**Gardziel, Z., Harasimiuk, M., Jezierski, W., Pawłowski, A., Zgłobicki, W., 2006**. Gully erosion in the western part of the Nałęczów Plateau (Lublin Upland) (in Polish with English summary). Przegląd Geologiczny, **54**: 768–776.

**Gawrysiak, L., 2019**. Segmentacje rzeźby terenu z wykorzystaniem metod automatycznej klasyfikacji rzeźby i ich relacja do mapy geomorfologicznej (in Polish). MCSU press, Lublin.

**Gawrysiak, L., Harasimiuk, M., 2012.** Spatial diversity of gully density of the Lublin Upland and Roztocze Hills (SE Poland). Annales UMCS, sec. B, **68**: 27–43. https://doi.org/10.2478/v10066-012-0002-y

**Gawrysiak, L., Kociuba, W., 2023.** LiDAR-derived relief typology of loess patches (East Poland). Remote Sensing, **15**: 1875. https://doi.org/10.3390/rs15071875

**Gilewska, S., Maruszczak, H., Mojski, E., Starkel, L., 1980.** Przeglądowa Mapa Geomorfologiczna Polski w skali 1:500 000, arkusz Lublin (in Polish). Instytut Geografii i Przestrzennego Zagospodarowania PAN, Kraków.

**Haase, D., Fink, J., Haase, G., Ruske, R., Pécsi, M., Richter, H., Altermann, M., Jäger, K.-D., 2007**. Loess in Europe—its spatial distribution based on a European Loess Map, scale 1:2,500,000. Quaternary Science Reviews, **26**: 1301–1312. https://doi.org/10.1016/j.quascirev.2007.02.003

**Harasimiuk, M., Henkiel, A., 1976.** Peculiarities of the loess cover in the western part of the Nałęczów Plateau (in Polish with English summary). Biuletyn Instytutu Geologicznego, **297**: 177–181.

**Harasimiuk, M., Henkiel, A., 1978a.** The influence of the geological structure and of the substratum relief on the configuration of loess cover in the area of the western part of the Nałęczów Plateau (in Polish with English summary). Annales UMCS, sec.B, **30/31**: 55–80.

**Harasimiuk, M., Henkiel, A., 1978b.** Szczegółowa Mapa geologiczna Polski w skali 1:50 000, ark. Łęczna – 0750 (in Polish). NAG, Państwowy Instytut Geologiczny – PIB, Warszawa.

**Harasimiuk, M., Henkiel, A., 1981.** Fossil valley forms in the vinicities of Łęczna and their importance for paleogeography of the Wieprz river drainage system (in Polish with English summary). Kwartalnik Geologiczny, **25** (1): 147–161.

**Hu, G., Dai, W., Li, S., Xiong, L., Tang, G., 2020.** A vector operation to extract second-order terrain derivatives from digital elevation models. Remote Sensing, **12**: 3134. https://doi.org/10.3390/rs12193134

**Jary, Z., 1991.** Gully erosion on Głubczyce Upland (in Polish with English summary). Acta Universitatis Wratislaviensis 1237, Prace Instytutu Geograficznego, ser. A, **6**: 131–151.

**Jary, Z., Kida, J., 2002.** Gully erosion on loess areas of SW Poland (in Polish with English summary). Zeszyty Problemowe Postępów Nauk Rolniczych, **487**: 79–86.

**Jasiewicz, J., Stepinski, T., 2013.** Geomorphons – a pattern recognition approach to groupification and mapping of landforms. Geomorphology, **182**: 147–156. https://doi.org/10.1016/j.geomorph.2012.11.005

**Jersak, J., Sendobry, K., Śnieżko, Z., 1992**. Evolution of loess covers in Poland during the Post-Warta period (in Polish with English summary). Prace Naukowe Uniwersytetu Śląskiego, Katowice, **1227**: 1–200.

**Jiang, C., Fan, W., Yu, N., Nan, Y., 2021.** A new method to predict gully head erosion in the Loess Plateau of China Based on SBAS-InSAR. Remote Sensing, **13**: 421. https://doi.org/10.3390/rs13030421

**Józefaciuk, Cz., Józefaciuk, A., 1992.** Gully densities in physico-geographical units of Poland (in Polish with summary in English). Pamiętnik Puławski suplement, **101**: 51–66.

**Kendall, M.G., 1948.** Rank Correlation Methods. Charles Griffin and Company Limited, Londyn.

**Kęsik, A., 1961.** Vallées des Terrains Loessiques de la Partie Quest du Plateau de Nałęczów. Annales UMCS Sec. B., **15**: 123–155.

**Kida, J., 1996.** Some features of loess relief of the Opole region (in Polish with English summary). Acta Universitatis Wratislaviensis 1808, Prace Instytutu Geograficznego, ser. A, **8**: 43–61.

**Kołodyńska-Gawrysiak, R., 2019a.** Holocene evolution of closed depressions and its relations to landscape dynamics in the loess areas of Poland. Holocene, **29**: 543–564. https://doi.org/10.1177/0959683618824792

**Kołodyńska-Gawrysiak, R., 2019b**. The impact of palaeorelief on the origin of some closed depressions in loess areas in the Lublin Upland (Eastern Poland). Polish Journal of Soil Science, **52**: 1–12. https://doi.org/10.17951/pjss/2019.52.1.1

**Kołodyńska-Gawrysiak, R., Chabudziński, Ł., 2012.** Morphometric features and distribution of closed depression on the Nałęczów Plateau (Lublin Upland, SE Poland). Annales UMCS sec. B, **67**: 45–61.

**Kołodyńska-Gawrysiak, R., Chabudziński, Ł., 2014.** The types and function of closed depressions in modern loess landscape on Nałęczów Plateu (Lublin Upland, E Poland). Annales UMCS sec. B, **69**: 61–77.

**Kołodyńska-Gawrysiak, R., Poesen, J., 2017.** Closed depressions in the European loess belt – natural or anthropogenic origin? Geomorphology, **288**: 111–128. https://doi.org/10.1016/j.geomorph.2017.02.004

**Kołodyńska-Gawrysiak, R., Gawrysiak, L., Budzyński, A., Gardziel, Z., 2011.** Road gullies of the Lublin Upland and Roztocze region and methods of their protection against destruction (in Polish with English summary). Annales UMCS sec. B, **66**: 29–47. https://doi.org/10.2478/v10066-011-0011-2

**Kołodyńska-Gawrysiak, R., Harasimiuk, M., Chabudziński, Ł., Jezierski, W., 2018.** The importance of geological conditions for the formation of past thermokarst closed depressions in the loess areas of eastern Poland. Geological Quarterly, **62** (3): 685–704. https://doi.org/10.7306/gq.1431

**Kołodyńska-Gawrysiak, R., Trzciński, J., Zaremba, M., Mroczek, P., 2019.** Grain-size and microstructure of the loess from closed depressions in the Nałęczów Plateau (East Poland). Polish

Journal of Soil Science, **52**: 295–325.
https://doi.org/10.17951/pjss/2019.52.2.295

**Lehmkuhl, F., Bösken, J., Hošek, J., Sprafke, T., Marković, S.B., Obreht, I., Hambach, U., Sümegi, P., Thiemann, A., Steffens, S., Lindner, H., Veres, D., Zeeden, Ch., 2018**. Loess distribution and related Quaternary sediments in the Carpathian Basin. Journal of Maps, **14**: 661–670.
https://doi.org/10.1080/17445647.2018.1526720

**Lehmkuhl, F., Nett, J.J., Pötter, S., Schulte, P., Sprafke, T., Jary, Z., Antoine, P., Wacha, L., Wolf, D., Zerboni, A., Hošek, J., Marković, S.B., Obreht, I., Sümegi, P., Veres, D., Zeeden, C., Boemke, B., Schaubert, V., Viehweger, J., Hambach, U., 2021.** Loess landscapes of Europe – mapping, geomorphology, and zonal differentiation. Earth-Science Reviews, **215**: 103496
https://doi.org/10.1016/j.earscirev.2020.103496

**Li, Y., Shi, W., Aydin, A., Beroya-Eitner, M.A., Gao, G., 2020a.** Loess genesis and worldwide distribution. Earth-Science Reviews, **201**: 102947.
https://doi.org/10.1016/j.earscirev.2019.102947

**Li, S., Xiong, L., Tang, G., Strobl, J., 2020b.** Deep learning-based approach for landform classification from integrated data sources of digital elevation model and imagery. Geomorphology, **354**: 107045. https://doi.org/10.1016/j.geomorph.2020.107045

**Lindner, H., Lehmkuhl, F., Zeeden, C., 2017**. Spatial loess distribution in the eastern Carpathian Basin: a novel approach based on geoscientific maps and data. Journal of Maps, **13**: 173–181.
https://doi.org/10.1080/17445647.2017

**Marks, L., Ber, A., Gogołek, W., Piotrowska, K., 2006**. Geological Map of Poland 1:500 000 with Explanatory Text – south-eastern part. NAG, Państwowy Instytut Geologiczny – PIB, Warszawa.

**Maruszczak, H., 1954.** Dolinen auf Lössgebieten der Lubliner Hochfläche (in Polish with German summary). Annales UMCS sec. B, **8**: 123–268.

**Maruszczak, H., 1958.** Characteristic relief forms of the loess area within the Lublin Upland (in Polish with English summary). Czasopismo Geograficzne, **29**: 335–354.

**Maruszczak, H., 1961.** Le relief des terrains de loess sur le Plateau de Lublin. Annales UMCS, sec.B, **15**: 93–130.

**Maruszczak, H., 1963**. Warunki geologiczno-geomorfologiczne rozwoju erozji gleb w południowej części województwa lubelskiego (in Polish). Wiadomości Instytutu Melioracji i Użytków Zielonych, **3**: 19–44.

**Maruszczak, H., 1973**. Gully erosion in the eastern part of southern uplands of Poland (in Polish with English summary). Zeszyty Problemowe Postępów Nauk Rolniczych, **151**: 15–30.

**Maruszczak, H., 1987**. Loesses in Poland, their stratigraphy and paleogeographical interpretation. Annales UMCS sec. B, **41**: 15–54.

**Maruszczak, H., 1991.** General features of the loesses in Poland (in Polish with English summary). In: Podstawowe profile lessów w Polsce, **1** (ed. H. Maruszczak): 1–12. UMCS, Lublin.

**Maruszczak, H., 1995**. Glacial cycles of loess accumulation in Poland during the last 400 ka and global rhythms of paleogeographical events. Annales UMCS, sec. B, **50**: 127–156.

**Maruszczak, H., 2001**. Main sections of loesses in Poland (in Polish with English summary). In: Podstawowe profile lessów w Polsce, **2** (ed. H. Maruszczak). UMCS, Lublin.

**Maruszczak, H., Michalczyk, Z., Rodzik, J., 1984.** Geomorphologic and hydrogeologic conditions for denudation development in the Grodarz drainage basin, Lublin Upland (in Polish with English summary). Annales UMCS, sec. B, **39**: 117–145.

**Moskal-del Hoyo, M., 2021**. Open canopy forests of the loess regions of southern Poland: a review based on wood charcoal assemblages from Neolithic and Bronze Age archaeological sites. Quaternary International, **593/594**: 204–223.
https://doi.org/10.1016/j.quaint.2020.11.013

**Pécsi, M., 1990**. Loess is not just the accumulation of dust. Quaternary International, **7/8**: 1–21.

**Pike, R.J., Wilson, S.E., 1971**. Elevation-relief ratio, hypsometric integral, and geomorphic area-altitude analysis. Geological Society of America Bulletin, **82**: 1079–1084.
https://doi.org/10.1130/0016-7606(1971)82[1079:ERHIAG]2.0.CO;2

**Popov, D., Marković, B.S., Jovanović, M.A., Mesaroš, M.A., Arsenović, D.A., Stankov, U.A, Gubik, D.B., 2012**. Geomorphological investigations and GIS approach of the Tamiš Loess Plateau, Banat Region (Northern Serbia). Geographica Pannonica, **16**: 1–9.

**Pożaryski, W., Maruszczak, H., Lindner, L., 1994**. Development of the Pleistocene valley of the middle Vistula river, considering especially its gap in the South Polish Uplands (in Polish with English summary). Przegląd Geologiczny, **42**: 523–531.

**Rejman, J., Rafalska-Przysucha, A., 2015**. Ocena wielkości erozji i akumulacji na podstawie rekonstrukcji profili glebowych w lessowym obszarze Działów Grabowieckich (Wyż. Lubelska) (in Polish). Kongres Geografów Polskich „Granice Geografii", Lublin, 17–21.06.2015.

**Rodzik, J., 2008**. Wpływ deszczów ulewnych i roztopów na rozwój wąwozu lessowego (in Polish). Landform Analysis, **8**: 56–59.

**Rodzik, J., Janicki, G., Zagórski, P., Zgłobicki, W., 1998**. Heavy rainfalls in the Lublin Uppland and their effect on relief of loess areas (in Polish with English summary). Dokumentacja Geograficzna, **11**: 45–68.

**Rodzik, J., Furtak, T., Paluszek, J., Rejman, J., 2005**. Some aspects of soil transects use in assessment of soil erosion (in Polish with English summary). Acta Agrophysica, **5**: 401–407.

**Rzechowski, J., Cieśliński, S., Marszałek, S., 2009**. Szczegółowa Mapa Geologiczna Polski w skali 1:50 000, ark. Hrubieszów – 0864 (in Polish). NAG, Państwowy Instytut Geologiczny – PIB, Warszawa.

**Schmitt., A., Rodzik, J., Zgłobicki, W., Russok, Ch., Dotterweich, M., Bork, H.-R., 2006.** Time and scale of gully erosion in the Jedliczny Dol gully system, south-east Poland. Catena, **68**: 124–132. https://doi.org/10.1016/j.catena.2006.04.001

**Solon, J., Borzyszkowski, J., Bidłasik, M., Richling, A., Badora, K., Balon, J., Brzezińska-Wójcik, T., Chabudziński, Ł., Dobrowolski, R., Grzegorczyk, I., Jodłowski, M., Kistowski, M., Kot, R., Krąż, P., Lechnio, J., Macias, A., Majchrowska, A., Malinowska, E., Migoń, P., Myga-Piątek, U., Nita, J., Papińska, E., Rodzik, J., Strzyż, M., Terpiłowski, S., Ziaja, W., 2018**. Physio-geographical mesoregions of Poland – verification and adjustment of boundaries on the basis of contemporary spatial data. Geographia Polonica, **91**: 143–169.
https://doi.org/10.7163/GPol.0115

**Superson, J., Rodzik, J., Reder, J., 2014**. Natural and human influence on loess gully catchment evolution: a case study from Lublin Upland, E Poland. Geomorphology, **212**: 28–40.
https://doi.org/10.1016/j.geomorph.2013.09.011

**Yuan, S., Xu, Q., Zhao, K., Wang, X., Wang, C., 2020**. Geomorphological classification and evolution of plateau-beam-loess hills in Heshui county of the east Gansu province. Geographical Research, **39**: 1920–1933.
https://doi.org/10.11821/dlyj020190988

**Yuan, S., Xu, Q, Zhao, K., Wang, X., Zhou, Q., Chen, W., Pu, Ch., Li, H., Kou, P., 2022**. Loess tableland geomorphic classification criteria and evolutionary pattern using multiple geomorphic parameters. Catena, **217**: 106493.
https://doi.org/10.1016/j.catena.2022.106493

**Wągrowski, A., 1996.** Szczegółowa Mapa Geologiczna Polski w skali 1:50 000, ark. Turobin – 0859 (in Polish). NAG, Państwowy Instytut Geologiczny – PIB, Warszawa.

**Wei, H., Li, S., Li, C., Zhao, F., Xiong, L., Tang, G., 2021**. Quantification of Loess Landforms from Three-Dimensional Landscape Pattern Perspective by Using DEMs. ISPRS International Journal of Geo-Information, **10**: 693.
https://doi.org/10.3390/ijgi10100693

**Xiong, L., Tang, G., Li, F., Yuan, B., Lu, Z., 2014.** Modeling the evolution of loess-covered landforms in the Loess Plateau of China using a DEM of underground bedrock surface. Geomorphology, **209**: 18–26. https://doi.org/10.1016/j.geomorph.2013.12.009

**Xiong, L., Zhu, A., Zhang, L., Tang, G., 2018.** Drainage basin object-based method for regional-scale landform groupification: a case study of loess area in China. Physical Geography, **39**: 523–541. https://doi.org/10.1080/02723646.2018.1442062

**Zgłobicki, W., 2002**. Geochemical record of human activity in slope and river sediments (in Polish with English summary). MCSU Press, Lublin.