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Geomorphometric diversity of closed depressions in the loess belt of east Poland (Nałęczów Plateau)

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Abstract—**Closed depressions (CDs, Fig. 1B) are typical geomorphological features of the loess belt in Europe. Although they are important elements of loess landscape in Europe, these depressions have been subject to no comprehensive studies of their geomorphometric properties. This paper presents a detailed case study of CDs in a loess region of east Poland (Nałęczów Plateau, Fig. 1A) investigating their morphometric features for a better understanding of the geodiversity of loess landscapes.**

The objective of the study was (1) the development of a methodology of delimitation of closed depressions and their watersheds, and (2) the analysis of their selected geomorphometric parameters in reference to land cover described in CLC2018. The detailed investigation concerned the Nałęczów Plateau (493.7km^2, east Poland) with a loess cover, where closed depressions are common elements of land relief. The extraction of depressions employed a high resolution (1x1 m) Digital Terrain Model; and the calculations were performed in SAGA-GIS and ArcGIS software. The calculation results were used for a quantitative description of the investigated landforms. Finally, Pearson correlation coefficients were calculated using pairs of parameters characterising depressions and watersheds in order to estimate correlations between them.

High diversity of CDs varying in size, length, depth, volume, and circularity ratio was found. Their watersheds also varied in terms of these parameters. Differences between CDs on agricultural land and in forests were determined. Part of these parameters were mutually correlated. The obtained results will be useful in describing the functioning of processes in other disciplines.

I. INTRODUCTION

A closed depression (CD) is a landform where the hillslopes encircle a common sediment depository, and the sediment eroded from the hillslopes by water and tillage erosion is trapped in the system [8]. Closed depressions (CDs) are typical geomorphological features of the loess belt in Europe as well as other loess regions in the World. The origin and evolution of CDs are highly debated in literature (see review in [3]). However, no comprehensive study of the geomorphic properties of these depressions has been made. Literature on the morphology of CDs is sparse, but several studies reported the basic dimensions of these landforms [3]. Preliminary research of detailed morphometric features of CDs was conducted in the loess areas of east Poland (Nałeczów Plateau) by Kołodyńska-Gawrysiak and Chabudziński [4, 5] and by Kołodyńska-Gawrysiak et al.[6] for better understanding of their origin and evolution. The Nałęczów Plateau (493.7 km^2) is covered by a compact loess belt of a differential thickness up to more than 20 m, and CDs are the primary element of its land relief.

The objective of this paper is to characterise the morphometric features of CDs in the Nałeczów Plateau to better recognise and understand the geodiversity of loess landscapes.

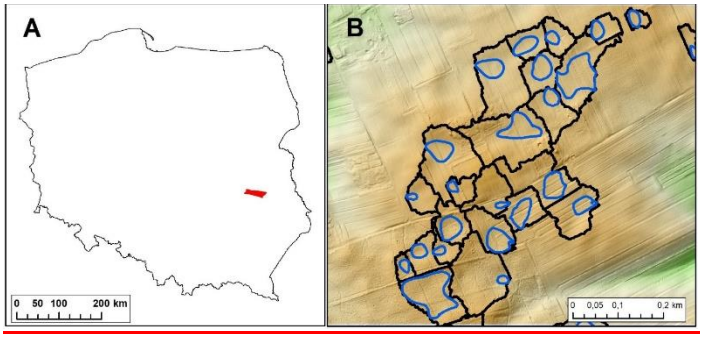

Figure 1. Location of the Nałęczów Plateau in Poland (A), and an example of closed depressions and their watersheds (B).

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II. DATA AND METHODS

The analysis was based on a Digital Terrain Model (DTM) developed during project ISOK, including LiDAR scanning of Poland in the years 2011-2014 [9]. The DTM has a high spatial resolution of 1x1 m and vertical accuracy of 0.15 m [7]. Land cover was defined by means of CLC2018.

The Extraction of CDs from DTM employed the Closed Depressions function, included in the Basic Terrain Analysis module of SAGA-GIS [1]. The result was a grid of data containing all non-drainage surfaces with strongly differential areas. The visual analysis showed that cells defining depressions are grouped into areas of varying size, shape, and compactness. We noticed that landforms with an area of more than 200 m^2 are clearly isolated as compact areas. The next stage of processing involved the extraction of such landforms. Then, grid data were converted to vector polygons (shapefile), and depressions of anthropogenic origin were manually removed based on knowledge from field investigations and detailed analyses of their morphology and position in land relief. Shaded relief and coloured DTM were useful at this stage.

Next, the shape of polygons was smoothed using the "smooth polygon" tool (ArcGIS). Several attempts were made to find the optimum value of smoothing tolerance, and 30 m was eventually accepted. After smoothing, small artefacts were removed manually from some polygons. Finally, clear polygon data were analyzed by calculating the following: (1) area, (2) circularity ratio (Rk) [2], (3) depth, (4) volume, and (5) maximum length understood as diameter of circle enveloping polygon. Information concerning CLC2018 necessary to compare indices for areas of different types of land cover was assigned to polygons.

The next step was delimiting borders of watersheds of depressions by means of the "watershed tool" (ArcGIS), where polygons defining depressions were declared as pour points. The resulting grid data were converted to vector polygons (shapefile), and then morphometric indices were calculated, namely: (1) area, (2) circularity ratio (Rk), and (3) height difference within watershed.

The last stage was calculating Pearson correlation coefficients for pairs of indices of depressions, and between indices of depressions and watersheds.

III. RESULTS

A. Closed depressions

We distinguished 5419 closed depressions within the study area, with an area ranging from 0.02 to 3.66 hectares (Tab. 1). Landforms with an area of less than 0.1 ha (63.4%) were the most numerous. We found 236 (4.3%) largest forms with an area exceeding 0.5 ha. The total area of depressions was 7.5 km^2, accounting for 1.51% coverage of the Nałęczów Plateau. Depressions were the most common (Tab. 2) in agricultural areas (CLC code: 211, 222, 231, 242, 243) – 4412 landforms, constituting 81.4% of their total number (agriculture areas cover 72.75% of the Plateau). In forests (code 311, 312, and 313), we found 531 depressions (9.95%). Another outstanding land cover form was "discontinuous urban fabric" where we found 377 depressions (6.95%). In other categories (121, 122, 142, 222, and 231) depressions were not abundant (3.08%).

The average area of depressions in agricultural areas was 0.14 ha with a maximum of 3.46 ha. They were evidently smaller in forests, averaging 0.1 ha, although the largest depression (3.66 ha) was located in a forest.

TABLE 1. STATISTICS OF AREA (HA) OF CLOSED DEPRESSIONS

Range	0-0.05	0.05-0.10	0.10-0.15	0.15-0.20	0.20-0.25	0.25-0.30	0.30-0.35	0.35-0.40	0.40-0.45	0.45-0.50	> 0.50
Number	2006	1429	681	373	250	143	121	78	67	36	236

TABLE 2. DISTRIBUTION OF CLOSED DEPRESSIONS DUE TO CLC2018

class	112	121	122	142	211	222	231	242	243	311	312	313
number	377	7	105	9	3822	34	12	487	169	499	16	24

CLC2018 classes: 112 – Discontinuous urban fabric, 121 – Industrial or commercial units, 122 – Road and rail networks and associated land, 142 – Sport and leisure facilities , 211 – Non-irrigated arable land, 222 – Fruit trees and berry plantations, 231 – Pastures, 242 – Complex cultivation patterns, 243 – Land principally occupied by agriculture, with significant areas of natural vegetation, 311 – Broad-leaved forest, 312 – Coniferous forest, 313 – Mixed forest.

The depth of depressions (Tab. 3) was usually smaller than 1 m (5030 polygons, 92%), whereas the depth of most of them was in a range of 0.3-0.4 m (1068, 19.7%). The average depth of depressions was 0.49 m. 22 (0.4%) of them were classified as deepest (more than 2 m), with a maximum depth of 2.89 m. Depressions in agricultural areas had an average depth of 0.47 m. They were somewhat deeper in forests (average 0.61 m), and the deepest one (2.89 m) was located in a forest. Notice that the first category (0-0.2 m) includes shallow forms. Because of the vertical accuracy of the DTM (0.15 m) used in the analysis, some of them might be marked incorrectly. They constitute approximately 10% of the total number of CDs.

TABLE 3. DEPTH (M) OF CLOSED DEPRESSIONS

Range	0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0	1.0-1.2	1.2-1.4	1.4-1.6	1.6-1.8	1.8-2.0	>2.0
Number	581	2113	1275	692	369	171	98	50	33	16	22

The distribution of values (Tab. 4) of the circularity ratio (Rk) suggests that polygons of oval shape were most common. The mean value of Rk was 0.78, maximum reached 0.99, and minimum was 0.25. The largest, most complex polygons had an Rk value of approximately 0.5. The lowest values of the index

belonged to smaller polygons, usually with an area of less than 1000 m^2. Depressions in forests had a higher mean value of Rk (0.83) than those in agricultural areas (0.78).

TABLE 4. CIRCULATORY RATIO (RK) OF CLOSED DEPRESSIONS

Range	≤ 0.40	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-0.9	0.9-1
Number	67	188	403	730	1178	1630	1224

The maximum length of depressions (Tab. 5) was in a range between 16.9 and 355.7 m. The mean value was 50.1 m. The most frequent interval was 25-30 m (14.4%). Landforms with a length of up to 50 m were dominant (66.2%). We found 116 longest polygons with more than 150 m, accounting for 2.1%. The average length of depressions in forests was 40.4 m, and in agricultural areas 50.9 m.

TABLE 5. MAXIMUM LENGTH OF CLOSED DEPRESSIONS (M).

Range	< 20	20-40	40-60	60-80	80-100	100-120	120-140	140-160	>160
Number	131	2576	1445	589	288	164	88	42	97

The volume of closed depressions (Tab. 6) reached 38 123.1 m^3. The lowest value was 5.6 m^3, and mean 555.3 m^3. Depressions with a volume of up to 100 m^3 were dominant (44.5%), and large depressions (exceeding 1000 m^3) were relatively abundant (611, 11.3%). The mean volume of depressions throughout the study area was approximate to that in agricultural areas, and equaled 554.2 m^3. In forests the mean value was lower – 420.9 m^3. The depression with the largest area also had the highest volume (38,123 m^3).

TABLE 6. VOLUME (M3) OF CLOSED DEPRESSIONS

Range	0-100	100-200	200-300	300-400	400-500	500-600	600-700	700-800	800-900	900-1000	>1000
Number	2412	895	446	287	214	153	147	96	88	69	611

B. Watersheds

The area of watersheds (Tab. 7) varied from 0.037 to 20 hectares, averaging 0.97 ha. The most frequent class was 0-0.5 ha (43.2%), and watersheds with an area of up to 1 ha accounted for 71.1%. Watersheds of depressions in agricultural land had a mean area of 0.99 ha. It was considerably lower in forests, reaching 0.67 ha. The largest watershed in forests had an area of 9.36 ha. Watersheds in the class of over 5 ha only constituted 1.9%. The total area of watersheds in the Nałęczów Plateau was 5.26 km^2 (10.67%).

TABLE 7. AREA (HA) OF WATERSHEDS OF CLOSED DEPRESSIONS

Range	0-0.5	0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5	2.5-3.0	3.0-3.5	3.5-4.0	4.0-4.5	4.5-5.0	>5.0
Number	2341	1513	692	304	171	120	71	47	33	21	105

The circularity ratio (Tab. 8) was considerably smaller than in the case of closed depressions, and reached 0.54, with a mean value of 0.30. The most frequent class was 0.30 0.35 (30.2%). Together with the lower (0.25 0.30) and higher (0.35 0.40) class, they accounted for 69.2%. The mean Rk value of watersheds in forests (0.31) was approximate to that in agricultural areas.

TABLE 8. CIRCULATORY RATIO (RK) OF WATERSHEDS OF CLOSED DEPRESSIONS

Range	≤0.10	0.10-0.15	0.15-0.20	0.20-0.25	0.25-0.30	0.30-0..35	0.35-0.40	0.40-0.45	0.45-0.50	> 0.50
Number	15	148	405	796	1233	1366	967	393	80	15

Height differences within watersheds (Tab. 9) were in a range of 0.26 22.98 m, with a mean value of 3.12 m. The most frequent class was 1 2 m (32.9%). Its frequency was approximate to that of class 2-3 m (32.2%). The highest class (> 10 m) included 1.97% of depressions. The greatest height difference (22.09 m) was determined for a watershed located in an agricultural area. Watersheds in agricultural areas had a lower (3.09 m) mean value than those in forests (3.27 m).

TABLE 9. HEIGHT DIFFERENCES (M) WITHIN WATERSHEDS.

Range	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	>10
Number	326	1486	1457	915	488	302	152	97	62	44	89

C. Correlation of parameters

The analysis of relations between parameters involved the calculation of Pearson correlation coefficients between parameters of depressions (Table 10), and between depressions and their watersheds (Table 11). High (important) values of coefficients were obtained for depressions in most cases of pairs of indices (6 to 10). In the case of indices of depressions to watersheds only 5 (out of 15) reached an important value – the area of depressions increased with the watershed area, and volume and maximum length were correlated with area and height differences within watersheds.

TABLE 10. PEARSON CORRELATION COEFFICIENTS BETWEEN PARAMETERS OF CLOSED DEPRESSIONS (BOLDED IMPORTANT VALUES)

	Depth	Rk	Volume	Length
Area	**0.69**	-0.30	**0.93**	**0.90**
Depth		-0.15	**0.64**	**0.74**
Rk			-0.23	-0.48
Volume				**0.76**

TABLE 11. PEARSON CORRELATION COEFFICIENTS BETWEEN PARAMETERS OF CLOSED DEPRESSIONS (CD) AND THEIR WATERSHEDS

Watershed / **CD**	Area	Depth	Rk
Area	**0.61**	0.25	-0.14
Depth	0.45	0.27	-0.08
Rk	-0.15	-0.02	0.16
Volume	**0.56**	**0.64**	-0.12
Length	**0.59**	**0.74**	-0.48

IV. CONCLUSIONS

The processing and analysis provided data for creating a database of closed depressions, their watersheds, and morphometric parameters in the Nałęczów Plateau. The application of a high resolution Digital Terrain Model permitted precise delimitation of all depressions, including those not subject to inventory so far. First, borders of watersheds of closed depressions were successfully delimited. The precise data provided the basis for the calculation of accurate morphometric parameters. They show high diversity of closed depressions and their watersheds. Closed depressions strongly vary in size (0.02-3.66 ha), depth (0.1-2.89 m), circularity ratio (0.25-0.99), length (16.9-355.7 m), and volume (5.6-38.123 m^3). We noticed differences in the morphology of depressions and watersheds in agricultural and forested areas, expressed in differences of values of the analysed parameters. CDs located in forests have smaller mean area and length, but are usually deeper and have more regular shape (higher Rk). Watersheds in agricultural areas are larger with a similar circularity ratio, and those in forests are somewhat deeper than those on agricultural land.

We noticed important correlations between most parameters of closed depressions and some for watersheds. Parameters of CDs are mutually corelated, except for the circularity ratio. In reference to the correlation of CDs and watersheds, only area/area, volume/area, volume/depth, length/area, and length/depth show significant correlation values.

Because the total area of non-drainage surfaces in the Nałęczów Plateau exceeds 10%, they presumably play an important role in the functioning of hydrological, geomorphological, and soil processes. CDs and their watersheds have been so far ignored in detailed investigations in these disciplines. Detailed data regarding the issue will improve the quality of research of loess areas.

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