

Morphology, hydrology and land use/land cover of closed depressions in the Zbrzyca River sub-catchment (northern Poland)

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Abstract: Closed depressions (CDs) are widespread geomorphological features of the young glacial landscapes of northern Poland; however, they remain insufficiently studied despite their important hydrological and ecological functions. This study aims to analyse the spatial distribution, morphometric characteristics, and land use/land cover (LULC) structure of closed depressions, distinguishing between infiltration (CD_I) and evapotranspiration (CD_E) forms, and to examine the relationships between their morphology and the surrounding landscape. The research was conducted in the Zbrzyca River sub-catchment, located in northern Poland. Spatial analyses were performed in a GIS environment using digital elevation model, cartographic materials, hydrographic datasets, and LULC databases. Morphometric parameters, including area, perimeter, denivelation, slope, and catchment development index, were calculated and compared between the two depression types. A total of 2,154 closed depressions were identified within the study area. Infiltration closed depressions were the dominant type, covering 108 km² (46.5% of the analysed catchment). They were generally more circular, steeper, and predominantly covered by forests and semi-natural vegetation. Evapotranspiration closed depressions occupied 31.5 km² (13.5% of the analysed catchment), were characterised by larger contributing areas and longer perimeters, and occurred mainly within agricultural landscapes. The spatial distribution of both depression types reflects the geological and geomorphological development of the catchment. These multifunctional geoecosystems play a key role in water retention, groundwater recharge, and biodiversity conservation. Their ecological significance and increasing anthropogenic pressure highlight the need for their effective protection and inclusion in sustainable land management and spatial planning strategies.

Keywords: geographical information system (GIS), geomorphological diversity, hydrological type, spatial analyses, topography, young glacial landscape

INTRODUCTION

Closed depressions (CDs) are terrain features characterised by their own catchments and the absence of surface outflow. A group of several such landforms constitutes a closed-drainage area, whose boundaries are defined by watershed divides (Drwal, 1975). In Poland, they are widespread and occur in both young

glacial landscapes (Major, Chudzińska and Majewski, 2024) and loess regions (Kołodziejka-Gawrysiak, 2017), where they occupy substantial areas.

In young glacial regions, their origin is linked to the activity of the Scandinavian Ice Sheet during the last Baltic glaciation, which shaped numerous hills, valleys, and CDs of diverse genesis (Liberacki, 1958; Galon, 1972). These forms may also have an

anthropogenic origin (Sobczyńska, 2015; Kołodyńska-Gawrysiak and Poesen, 2017), in areas affected by past military activities, they can develop as bomb craters (Payne *et al.*, 2018).

The literature reveals considerable terminological diversity regarding CDs, which typically function as evapotranspiration systems. They are referred to, among others, as “kettle holes” (Vasić *et al.*, 2020), “ponds” (Celcewicz and Gołdyn, 2021), “prairie potholes” (Johnson, Oslund and Hertel, 2008), “isolated wetlands” (Whigham and Jordan, 2023), or “karst depressions” (Pardo-Igúzquiza *et al.*, 2016). The choice of terminology depends primarily on regional context or genesis.

Interest in these landforms dates back to the late nineteenth century, when Keilhack (1891) described the occurrence of closed-drainage areas in Central Europe. Subsequent researchers, including Spethmann (1912) and Martonne de and Aufrère (1928), confirmed their widespread distribution. Martonne de and Aufrère (1928) introduced the concepts of “areism” and “endorheism” to describe areas lacking river drainage. In Poland, the study of CDs also has a long research tradition. This topic was further developed by Werner-Więckowska (1952), Werner-Więckowska (1953), Maruszczak (1954), Żynda (1959), Kowalska (1968) and Kowalska (1971), who analysed both the geomorphological processes leading to the formation of these closed landforms and the role of depressions in shaping the hydrological cycle. At that time, the concepts of “surface closed drainage” and “total closed drainage” were introduced. Recognition of the importance of CDs within the hydrographic structure was reflected in successive editions of the guidelines for the preparation of the “Hydrographic map of Poland at a scale of 1:50,000” (Klimaszewski, 1959; Celmer, 1964). These guidelines introduced a division into two types of depressions, and the term “surface endorheism” was replaced by the concept of an “infiltration closed depression”. The significance of the differentiated roles of CDs was formally established in “Guide for field hydrographic studies”, prepared at the request of the Hydrographic Commission of the Polish Geographical Society (Pol.: Komisja Hydrologiczna Polskiego Towarzystwa Geograficznego), in which Drwal (1989) ultimately distinguished between “infiltration closed depressions” (CD_I) and “evapotranspiration closed depressions” (CD_E).

From a hydrological perspective, CDs are important components of young glacial landscapes, functioning as natural accumulation zones for precipitation and snowmelt. Their presence contributes to delayed runoff and stabilises water regimes in catchments with poorly developed river networks (Soczyńska, 1997; Gerke *et al.*, 2010). They also influence local microclimatic conditions (Hayashi and Kamp van der, 2000). The functioning of these landforms strongly depends on their morphometric characteristics, such as area, depth, and slope gradients, which determine their retention capacity and water circulation dynamics (Hayashi and Kamp van der, 2000; Whigham and Jordan, 2003). In closed-basin lakes, interactions with groundwater are variable and may be either recharge- or discharge-dominated, depending on seasonal conditions (Nowicka and Lenartowicz, 2004).

An important research direction in the study of CDs is the systems-based approach initiated by Drwal (1974), in which depressions are treated as elements of a complex environmental system. Within this framework, the interplay among topography, hydrological conditions, substrate permeability, and vegetation

cover is key. Analysis of these components enables a more comprehensive understanding of the functioning of the entire geoecosystem. In subsequent years, research expanded to include ecological aspects, highlighting the role of depressions as geoecosystems (Major, 2010) that support biodiversity (Bedla and Kuczera, 2007; Rittenhouse and Semlitsch, 2007). Therefore, CDs can be considered as providers of multiple ecosystem services (Vasić *et al.*, 2020).

Studies of sediments infilling CDs provide insights into their origin and evolution. The presence of both mineral and biogenic deposits indicates a multi-stage development and underscores their importance as archives of environmental change (Micun, 2014; Karasiewicz and Juśkiewicz, 2017). Lithological variability reflects diverse depositional processes controlled by environmental conditions and landscape history (Forysiak *et al.*, 2017; Nitzsche *et al.*, 2017). In loess regions, the complex genesis of these forms and their value as records of Holocene environmental changes are particularly emphasised (Kołodyńska-Gawrysiak, 2017).

In recent years, digital tools such as Geographic Information Systems (GIS) and Digital Terrain Models (DTMs) have become increasingly important for analysing CDs. These tools enable detailed inventorying, spatial pattern analysis, and automated extraction of morphometric and functional parameters, significantly expanding research capabilities at the scale of entire catchments (Pardo-Igúzquiza and Dowd, 2021; Szafraniec, 2024; Esposito *et al.*, 2025).

Despite the growing number of studies, comprehensive approaches that integrate morphometric analysis, hydrological functioning, and contemporary land use/land cover (LULC) remain relatively scarce. In particular, the relationships between the physical characteristics of these forms and anthropogenic pressure, as expressed through LULC structure, remain insufficiently understood, limiting a more complete assessment of their role in young glacial landscapes.

In this context, this study aims to analyse the spatial structure and morphometric variability of CDs, distinguishing between CD_I and CD_E types, and to examine their relationships with LULC. The study focuses on the sub-catchment of the Zbrzyca River, located within a transitional zone between moraine islands and fluvio-glacial deposits formed during the recession of the Baltic glaciation ice sheet. This area is characterised by high natural value and lies within the buffer and transition zones of the “Bory Tucholskie” Biosphere Reserve. In this study, a CD is treated as a single geoecosystem encompassing both the depression and its contributing catchment, following the concept proposed by Major (2010).

The following study questions were formulated:

- what are the key morphometric differences between CD_I and CD_E?
- how are these types of CDs related to LULC?
- what do these relationships reveal about their contemporary hydrological functioning in a young glacial landscape?

The contribution of this study lies in integrating spatial datasets describing the physical characteristics of CDs. This approach enables the identification of relationships and spatial patterns that are not apparent in studies focused on individual aspects or conducted at smaller spatial scales. Consequently, it provides a more comprehensive understanding of the role of CDs in the functioning of young glacial landscapes.

MATERIAL AND METHODS

STUDY AREA

The study area is located in northern Poland, within the Zbrzyca River catchment, a left-bank tributary of the Brda River. The analysed section includes the upper and middle parts of the catchment up to the confluence with the Kulawa River and covers approximately 232.3 km². The area lies within the Charzykowy Plain and the Tuchola Forest, which form part of the South Pomeranian Lakeland (Solon *et al.*, 2018). It represents a typical young-glacial landscape, shaped during the Pomeranian phase of the last Baltic glaciation.

The terrain relief of the area is diverse, with extensive outwash surfaces and subglacial valleys as the dominant landforms. Older glacial landforms clearly control the present-day river network. In the central and southern parts, areas of undulating ground moraine occur, intersected by ridges of push moraines. A hummocky marginal zone and terminal moraine ridges dominate the northern part. In sections associated with the Zbrzyca River valley, Holocene floodplain terraces have developed. The entire area displays a mosaic-type relief (Fig. 1) (Szafranec, 2010). Elevations range from 121 to 206 m a.s.l.

Quaternary deposits, such as sands, gravels, and glacial tills, overlie Tertiary and Cretaceous sediments. Their thickness reaches up to 200 m (Jutrowska, 2007). Highly permeable sediments favour infiltration and groundwater recharge, whereas local occurrences of tills and clays limit groundwater flow and promote water retention (Pazdro and Kozerski, 1990). The youngest deposits are Holocene in age and fill various types of topographic depressions, both on outwash surfaces and on uplands. These include sands and gravels in river valleys, as well as fine-grained sands and lacustrine chalk that surround and infill lake basins and river valleys (Jutrowska, 2007).

The catchment is characterised by a dense hydrographic network composed of the Zbrzyca River, numerous lakes, small ponds, and intermittent streams. Flow-through ribbon lakes

dominate, along with small closed-basin dystrophic water bodies (Wysocka, 2005). Groundwater is most commonly confined. In the south-western part of the catchment, numerous springs confirm a strong hydraulic connection between surface water and groundwater (Nowicka, 2003).

The climate is temperate transitional, with a mean annual air temperature of approximately 8.0–8.5°C and annual precipitation totals of about 600–650 mm. Snow cover persists for roughly 40–50 days per year (Tomczyk and Bednorz, 2022). High air humidity prolongs waterlogging in topographic depressions.

Forests and seminatural areas and arable land occupy approximately 65% and 27% of the catchment area, respectively, while grasslands and peatlands occur mainly within river valleys. The diverse post-glacial landscape makes this area particularly suitable for studies on CDs.

ANALYSIS OF THE HYDROLOGICAL TYPE AND LAND USE/LAND COVER OF CLOSED DEPRESSION CATCHMENTS

Hydrological types and LULC catchments of CDs were analysed using ArcGIS for Desktop 10.8.2 (ESRI, 2021). Catchment boundaries were delineated based on 1:10,000 topographic maps obtained from the GUGiK WMS service.

Maps of CD_I and CD_E were prepared using two complementary approaches. In the first approach, catchment boundaries were overlaid with a surface-deposit permeability map. This map was compiled from a 1:50,000-scale map of surface deposits (Surface Deposits Map 1978a; 1978b; 1978c; 1987d) – sheets: Brusy, Karsin, Kościerzyna, Studzienice. Lithological units were assigned to permeability classes following the classification of Pazdro and Kozerski (1990) (Tab. 1). Deposits with hydraulic conductivity values exceeding 10⁻⁴ m·s⁻¹ were classified as permeable, while those with lower values were considered impermeable. Closed depressions were classified as CD_I when permeable deposits predominated beneath their bottoms, and as CD_E when impermeable deposits were dominant.

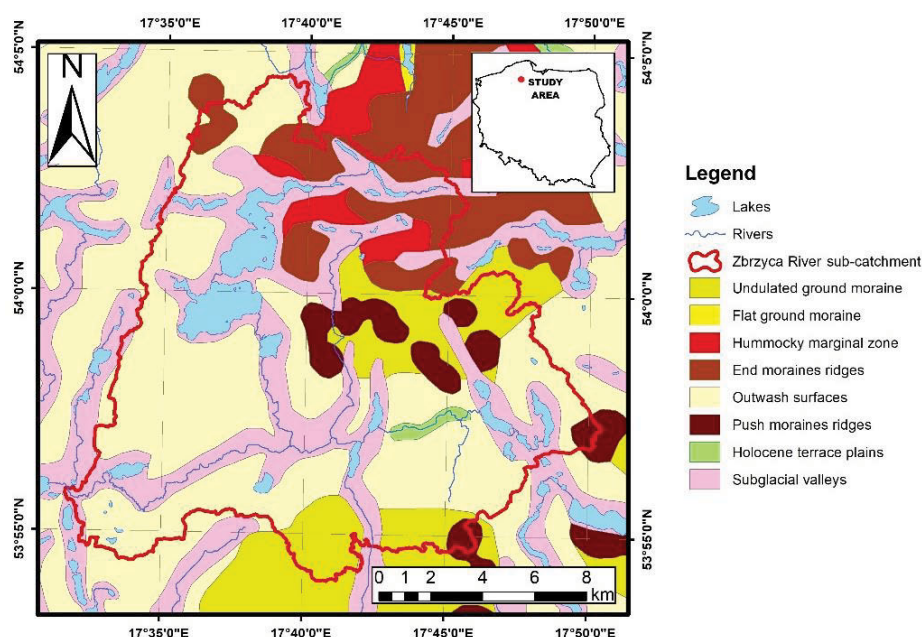


Fig. 1. Geomorphology of the study area; source: own elaboration based on Szafranec (2010)

Tabela 1. Permeability characteristics of surficial deposits occurring in the Zbrzyca River sub-catchment

Type of surficial deposits	Hydraulic conductivity k ($\text{m}\cdot\text{s}^{-1}$)	Permeability
Glacial till	10^{-8} – 10^{-6}	impermeable
Silt, sands, and lacustrine chalk	10^{-8} – 10^{-6}	
Peat	10^{-6} – 10^{-5}	
Mud deposits	10^{-6} – 10^{-4}	
Clay, silt and lake sands	10^{-4} – $>10^{-3}$	permeable
Fluvial sands and gravels	10^{-4} – $>10^{-3}$	
Sands and glaciofluvial gravels	10^{-4} – $>10^{-3}$	
Sands, gravels and boulders of terminal moraines	10^{-4} – $>10^{-3}$	
Sands, gravels and glacial boulders	10^{-4} – $>10^{-3}$	

Source: own elaboration.

In the second approach, catchment boundaries were analysed using data from the Hydrographic Map of Poland at a scale of 1:10,000 (HMP10) (Barszczyńska *et al.*, 2013), in its updated version (Grela *et al.*, 2017), together with data from the Topographic Objects Database (BDOT10k), developed in 2012–2013 in accordance with Ministry of the Interior and Administration guidelines (Rozporządzenie, 2011). The HMP10 provided information on surface water bodies and drainage ditches, whereas BDOT10k supplied data on wetlands. This combination of datasets allowed verification of the actual occurrence of wetlands, small water bodies, and lakes within the depressions (Fig. 2a). Depressions lacking any water body, drainage ditch, or wetland were classified as CD_I . In contrast, those containing such features were classified as CD_E (Fig. 2b). Depressions connected to surface outflow via drainage ditches were excluded from further analysis. Both classifications are based on desk analysis and have not been

validated in the field using hydrological measurements. It is also important to note that the second approach uses hydrological conditions corresponding to the state at the time the spatial datasets were developed, so seasonal variations in moisture conditions were not accounted for.

Land use/land cover within the CDs was identified through spatial analysis using BDOT10k LULC data. The original 23 BDOT10k categories were aggregated into seven LULC classes: artificial surfaces, arable land, meadows and pastures, fallow land, forest and seminatural areas, wetlands, and surface waters (Tab. 2), following the approach proposed by Kutyla (2020).

MORPHOMETRIC ANALYSIS OF CLOSED DEPRESSIONS

The morphometric analysis of the CDs was based on spatial analyses conducted in ArcGIS for Desktop 10.8.2 (ESRI, 2021), which enables efficient calculation of basic morphometric parameters of catchments (Bielczyńska and Kutyla, 2022). For all CDs, the following morphometric indices describing their size and shape were calculated: area (A), perimeter (P), maximum denivelation (ΔH), catchment development index (K), and mean catchment slope (J).

Catchment area and perimeter were calculated using the Calculate Geometry function. Terrain denivelation, defined as the elevation difference between the highest and lowest points within the catchment boundaries, was determined using a DTM derived from Light Detection and Ranging (LiDAR) data, with a spatial resolution of 1×1 m and a vertical accuracy of 0.2 m, applying the Zonal Statistics as Table tool. Terrain slopes were calculated from a slope map generated with the Slope function, using the same DTM. Water body areas were removed from the slope layer to prevent underestimating mean slope values and overestimating flat areas within the CD_E . Mean slope values were extracted in the same manner as relief, using the Zonal Statistics as Table tool. The development of the catchment was determined according to the Equation (1):

$$K = \frac{P}{2\sqrt{\pi \cdot A}} \quad (1)$$

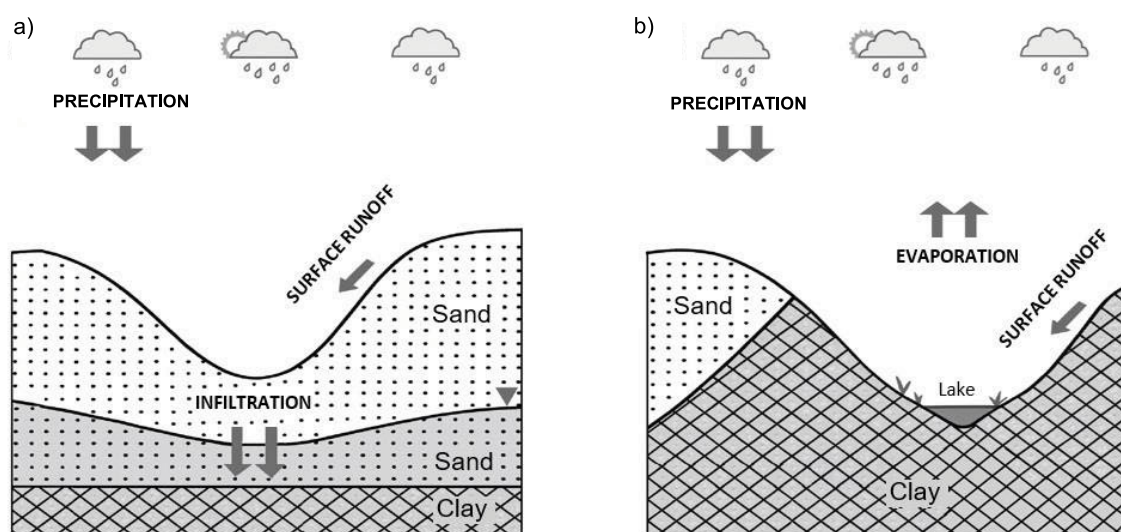


Fig. 2. Cross-section and simplified diagram of the water cycle in closed depressions: a) infiltration form (CD_I), b) evapotranspiration form (CD_E); source: Bajkiewicz-Grabowska and Mikulski (2006), modified

Table 2. Clustering of the land use/land cover classes according to BDOT10k to classes used in this study

Land use/land covers class according to BDOT10k	Land use/land cover class
Apartment buildings	artificial surfaces
Single-family homes	
Industrial and storage buildings	
Commercial and service buildings	
Other buildings	
Land under roads	
Land under railroads	
Place	
The area under technical devices or construction	
Industrial and storage area	arable lands
Allotment garden	
Plantation	
Orchard	
Cultivation on arable land	meadows and pastures
Grass vegetation	
Excavation sites	fallow lands
Forest	forests and seminatural areas
Groves	
Coppices	
Shrubs	
Inland marshes	wetlands
Inland wetlands	
Stagnant water	surface waters

Source: Kutyla (2020).

This index expresses the degree to which the catchment shape approaches a circle ($K = 1$). A modified classification after Lange (1993) was applied:

- 1.00–1.25 – low development,
- 1.26–1.75 – moderate development,
- >1.75 – high development.

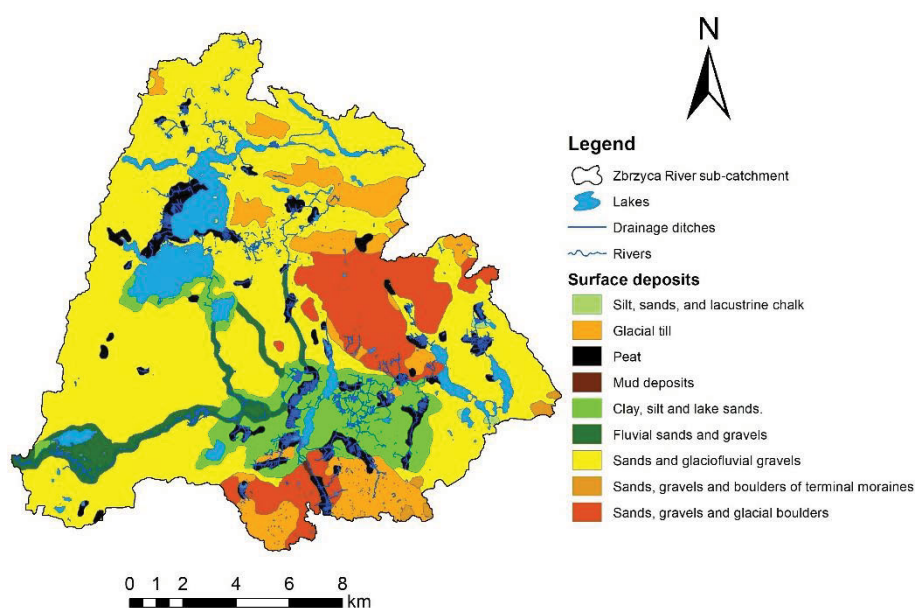
STATISTICAL ANALYSES

The distribution of morphometric parameters and CDs LULC, divided into CD_I and CD_E was presented using box-and-whisker plots. Data distribution normality was assessed using the Shapiro–Wilk test. Due to deviations from normality, comparisons of morphometric indices and LULC characteristics between CD_I and CD_E were performed using the nonparametric Mann–Whitney U test. Each analysed depression was treated as a separate unit to which a single, unambiguous hydrological type was assigned. It was therefore assumed that the observations approximately satisfied the independence assumption. At the same time, potential spatial autocorrelation arising from geomorphological conditions was accounted for. Similar types of depressions may co-occur within the same landform units, such as outwash plains or moraine areas, leading to spatial similarity among the analysed entities. All analyses were performed using Statistica 12 (StatSoft Inc., 2014).

RESULTS

PERMEABILITY OF SURFACE DEPOSITS

The dominant group of surface deposits in the study area consists of glaciofluvial and fluvial sands and gravels, covering about half of the area (Fig. 3). They occur mainly in the central part of the area and along valleys, forming zones of high permeability and promoting intensive infiltration. Approximately one quarter of the surface is occupied by sands, gravels, and boulders of end moraines and other glacial deposits, present, for example, in the

**Fig. 3.** Surface deposits map of the study area; source: own elaboration based on Surface Deposits Map (1978a; 1978b; 1978c; 1978c) – sheets: Brusy, Karsin, Kościerzyna, Studzienice

northern and south-western parts of the area. Their filtration properties are also high.

Glacial till deposits cover around 10% of the area and appear mainly in the western and southern parts of the catchment. Due to their low permeability, they limit infiltration and favour surface water retention. Lacustrine sediments such as silts, clays, sands, and lacustrine chalk occupy several percent of the surface, occurring, for instance, in the north-western and southern parts of the area. These deposits are impermeable or poorly permeable. Muds and peats form small patches, accounting for only a few percent of the area, and occur locally in depressions and along valley margins. Their very low permeability promotes water stagnation.

Overall, about 70–75% of the area is built of well-permeable deposits, while the remaining 25–30% consists of low-permeability soils that define zones of reduced infiltration (Fig. 4).

HYDROLOGICAL CHARACTERISTICS OF CLOSED DEPRESSIONS AND THEIR SPATIAL DISTRIBUTION

A large number of CDs were identified in the analysed part of the Zbrzyca River catchment. Based on 1:10,000 topographic maps, 2,154 such landforms were mapped. Their classification varied

depending on the source materials used. Data from the 1978 surface deposits map allowed the distinction of 1,814 CD_I and 340 CD_E (Fig. 5a). In contrast, the use of HMP10 and BDOT10k datasets resulted in an increase in the number of CD_I to 1,914, while the number of CD_E decreased to 240 (Fig. 5b). The results obtained from the second approach were adopted for further analyses.

This choice follows the definition proposed by Drwal (1975), who classifies CD_E as depressions with water present at the bottom, including small ponds, minor water bodies, wetlands, drainage ditches, or areas with a shallow water table. In contrast, CD_I are defined as depressions with a dry bottom and function as infiltration features.

Evapotranspiration closed depressions covers an area of 31.5 km², which corresponds to 13.5% of the total catchment area. Infiltration closed depressions occupy a much larger area of 108 km², representing 46.5% of the analysed Zbrzyca River catchment. The remaining part consists of exorheic areas covering 92.8 km², which is about 40% of the study area. Infiltration closed depressions are distributed throughout the entire catchment, whereas CD_E are concentrated mainly in the southern and north-eastern parts. Most CD_I occur within the Brda Outwash, while CD_E dominate on moraine uplands and within river valleys.

MORPHOMETRIC CHARACTERISTICS OF CLOSED DEPRESSIONS

The spatial structure of the morphometric parameters of CDs shows a mosaic pattern. Against this background, moraine island areas stand out clearly, as illustrated in Figure 6. Moreover, the comparison of results clearly confirms pronounced morphometric differences between CD_I and CD_E , including their size, shape, and topographic attributes (Tab. 3).

Evapotranspiration closed depressions are characterised by a larger area and perimeter, indicating a more extensive spatial form compared to CD_I . Differences in denivelation were also statistically significant, although less pronounced than those observed for size-related parameters (Fig. 7).

The K parameter, describing the degree to which a shape approaches a circular form, further confirmed the morphological contrast between the two types of depressions. Infiltration closed

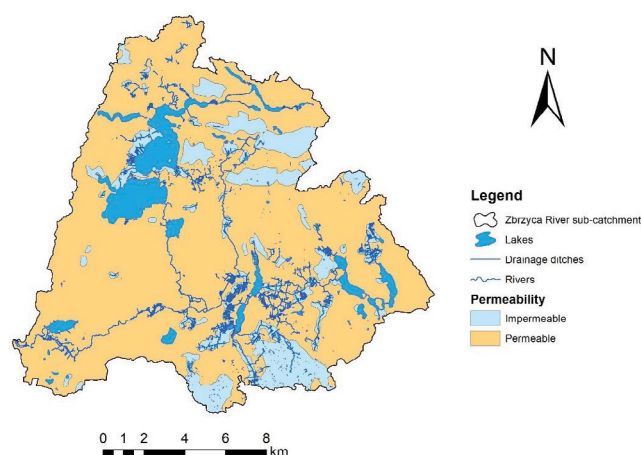


Fig. 4. Map of surficial deposit permeability in the study area; source: own study

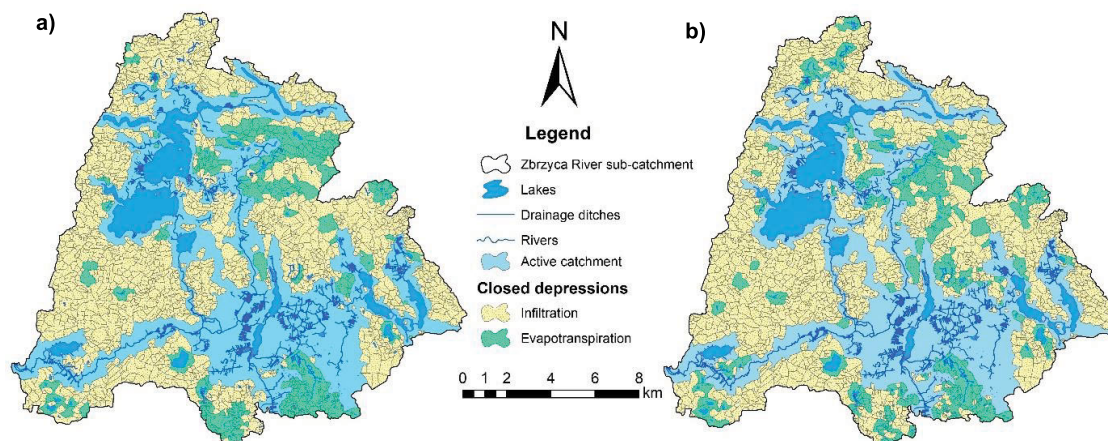


Fig. 5. Spatial distribution of closed depressions in the Zbrzyca River sub-catchment: a) based on Surface Deposits Map (1978a; 1978b, 1978c; 1988d), b) based on HMP10 (Barszczyńska *et al.*, 2013) and BDOT10k (Rozporządzenie, 2011); source: own study

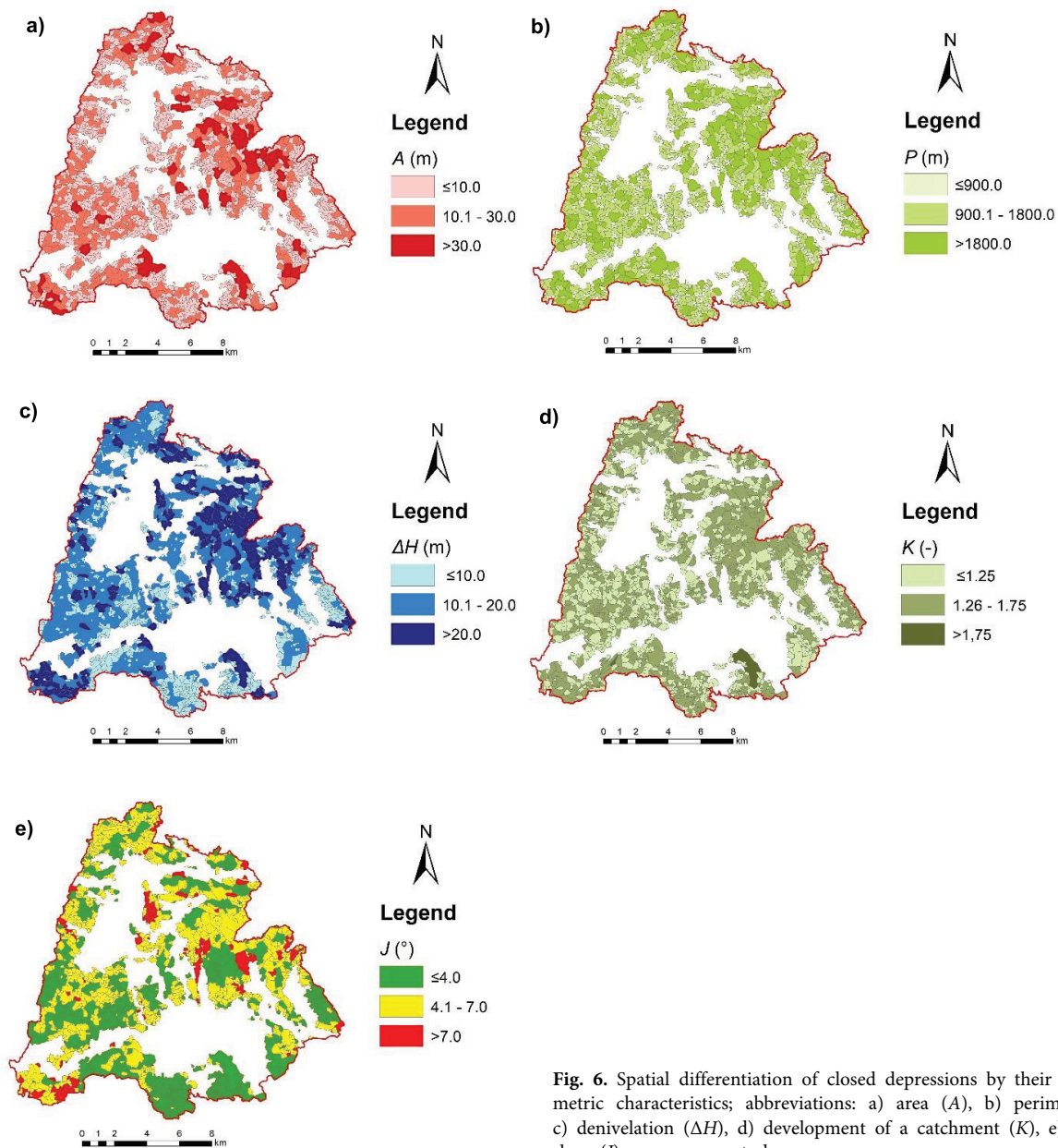


Fig. 6. Spatial differentiation of closed depressions by their morphometric characteristics; abbreviations: a) area (A), b) perimeter (P), c) denivelation (ΔH), d) development of a catchment (K), e) average slope (J); source: own study

depressions tends to be more circular than CD_E , which suggests a more regular geometry and weaker morphological development. Among the analysed variables, only the J parameter showed a higher median value for CD_I , suggesting differences in slope inclination. The effect size values ($|r|$) indicate that the observed differences between groups are generally small. For the analysed parameters, $|r|$ ranged from 0.07 to 0.18 (Fig. 7).

LAND USE/LAND COVER CHARACTERISTICS OF CLOSED DEPRESSIONS

Land use/land cover within the catchments of CDs showed clear, statistically significant differences between the hydrological types (Fig. 8). The weakest effect size was observed for artificial surfaces ($|r| = 0.19$). Higher effect sizes were obtained for meadows and pastures ($|r| = 0.27$) and arable lands ($|r| = 0.35$). The strongest effect size was found for forested and seminatural areas ($|r| = 0.44$), where the relationship with infiltration depressions

is the most pronounced. The $|r|$ values were not calculated for wetlands and surface water categories because they were absent in CD_I (Fig. 8).

In CD_I , forests and seminatural areas were dominant and, in many cases, covered the entire catchment. Arable land occurred much less frequently and on average occupied about 10% of the area. Other LULC forms were of marginal importance, with their share generally not exceeding 1.5%.

In CD_E , the LULC structure was distinctly different. Arable land dominated, with a mean share exceeding 50%. Forests and seminatural areas formed the second-largest category, showing very high variability, ranging from catchments entirely covered by forest and seminatural vegetation to those with no such LULC. The share of meadows and pastures usually did not exceed 8%. Owing to the nature of these depressions, wetlands and surface waters were also observed, occupying, on average, 0.5% and 2.6% of the area, respectively.

Table 3. Morphometric characteristics of closed depressions divided into infiltration and evapotranspiration

Morphometric characteristics		Infiltration closed depressions		Evapotranspiration closed depressions	
		<i>n</i>	%	<i>n</i>	%
<i>A</i> (ha)	≤10.0	1642	85.8	147	61.2
	10.1–30.0	256	13.4	66	27.5
	>30.0	16	0.8	27	11.3
	sum	1914	100.0	240	100.0
<i>P</i> (m)	≤900.0	1050	54.9	77	32.1
	900.1–1800.0	734	38.3	100	41.7
	>1800.0	130	6.8	63	26.3
	sum	1914	100.0	240	100.0
ΔH (m)	≤10	929	48.5	106	44.2
	10.1–20.0	793	41.4	80	33.3
	>20.0	192	10.1	54	22.5
	sum	1914	100.0	240	100.0
<i>K</i> (–)	≤1.25	1209	63.2	126	52.5
	1.26–1.75	699	36.5	113	47.1
	>1.75	6	0.3	1	0.4
	sum	1914	100.0	240	100.0
<i>J</i> (°)	≤4.0	839	43.8	138	57.5
	4.1–7.0	895	46.8	92	38.3
	>7.0	180	9.4	10	4.2
	sum	1914	100.0	240	100.0

Explanations: *n* = number of closed depressions, *A* = area, *P* = perimeter, ΔH = denivelation, *K* = development of a catchment, *J* = average slope. Source: own study.

DISCUSSION

Closed depressions are a permanent element of the landscape in young glacial areas of the temperate climate zone and occupy a substantial part of these regions (Major, 2010). They develop as a result of hydrological and geological processes and are characterised by the absence of natural surface outflow. Determining their spatial extent and spatial attributes is a key step in systemic analyses of these geomorphological forms (Drwal, 1982), including studies of water balance (Major, 2009) and sedimentation processes (Micun, 2014).

In recent years, Digital Terrain Models (DTMs) have increasingly been used to identify similar geomorphological features (Pardo-Igúzquiza and Dowd, 2021; Esposito *et al.*, 2025). It should be noted, however, that such approaches are most effective in areas with more pronounced relief, higher gradients, and greater denivelation. Automatic delineation of topographic catchments based on DTMs requires prior data processing, primarily the filling of spurious depressions that could interrupt simulated flow paths and artificially drain certain areas (Ufa, 2013; Lidberg *et al.*, 2017). This procedure does not allow true depressions to be distinguished from artefacts, potentially leading to the omission of small, genuine landforms. In addition, infrastructure elements such as bridges and roads crossing drainage structures may be represented as “digital dams” (Li *et al.*, 2013), artificially increasing the number of detected CDs. For these reasons, despite the availability of a high-resolution DTM with a vertical accuracy of 0.2 m, catchments in the present study were delineated using 1:10,000 topographic maps. This approach identified 2,154 landforms lacking surface outflow. The actual number would likely be higher; however, as observed in the Bory Tucholskie National Park by Nowicka (2016), a large proportion of evapotranspiration closed depressions (CD_E) forms have been drained as a result of land reclamation and

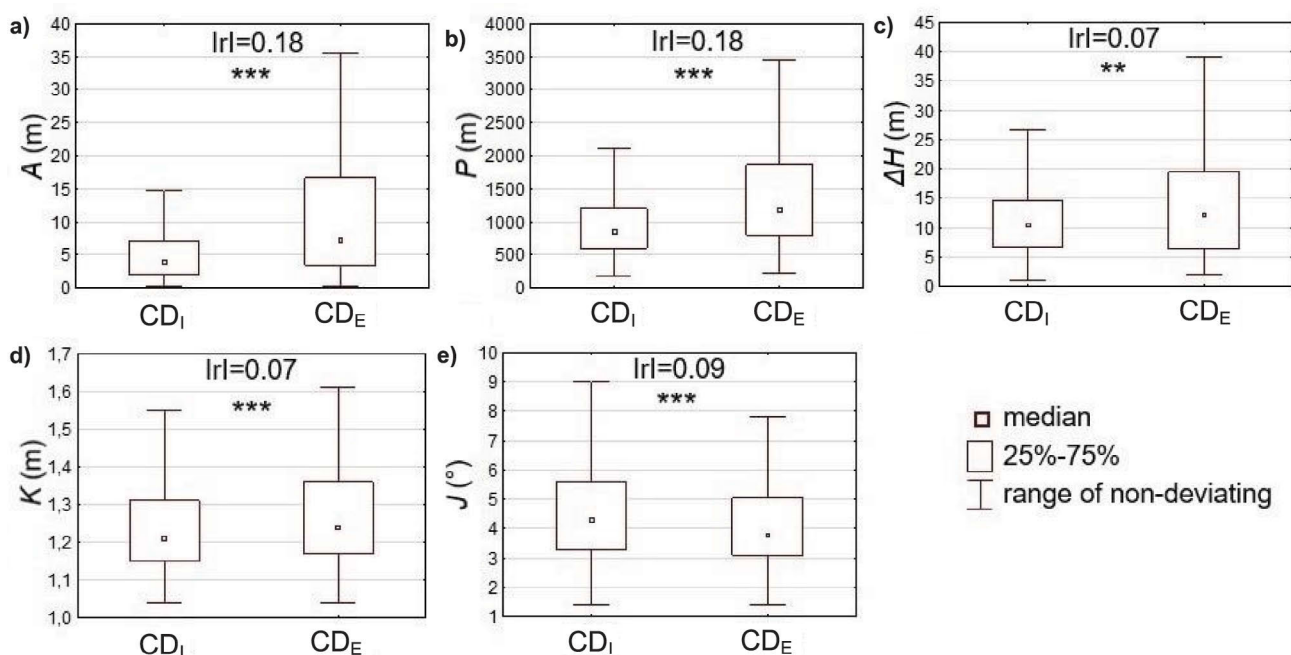


Fig. 7. Morphometric characteristics of infiltration (CD_I) and evapotranspiration (CD_E) closed depressions: a) area (*A*), b) perimeter (*P*), c) denivelation (ΔH), d) development of a catchment (*K*), e) average slope (*J*); significance level in the U Mann–Whitney test: *** $p \leq 0.001$, ** $p \leq 0.01$; $|r|$ = absolute value of size effect; source: own study

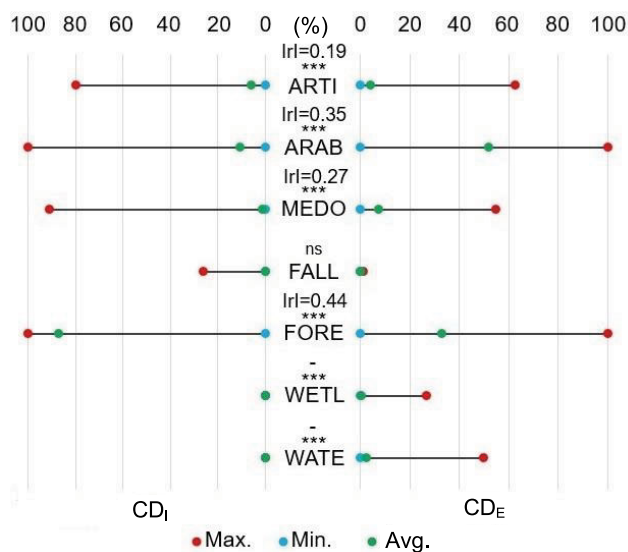


Fig. 8. Land use/land cover of infiltration (CD_I) and evapotranspiration (CD_E) closed depression; ARTI = artificial surfaces, ARAB = arable lands, FORE = forest and seminatural areas, MEDO = meadows and pastures, FALL = fallow lands, WETL = wetlands, WATE = surface waters, Avg. = average; significance level in the U Mann-Whitney test: *** $p \leq 0.001$, ns = non-significant; $|r|$ = absolute value of size effect; source: own study

incorporated into the direct drainage network. Vasić *et al.* (2020) note that issues related to the drainage of CDs are also observed in other countries, including Germany, the United States, and Canada.

According to Drwal (1975) and Gillijns, Poesen and Deckers (2005), the spatial distribution of CDs is controlled by the lithological mosaic of the area. This is consistent with the results obtained in the present study. Infiltration closed depressions are located predominantly on outwash surfaces built of highly permeable sands and gravels, whereas CD_E occur mainly on till deposits and lacustrine sediments. In some cases, CD_E appears in areas where surface deposits are mapped as highly permeable. This may partly result from the level of generalisation inherent to the map scale, but also, as noted by Nowicka (2016), from the presence of less permeable sediment lenses within otherwise permeable substrates, which locally impede infiltration.

Morphometric analysis indicates that CD_E landforms are generally larger than infiltration closed depressions (CD_I) forms. They are characterised by longer perimeters, greater denivelation, and gentler slopes, whereas CD_I more frequently exhibit near-circular shapes. These differences primarily reflect the conditions under which these forms developed during the retreat of the ice sheet, where a key role was played by the burial depth of dead ice, which controlled the subsequent degree of hollowing and thus the magnitude of denivelation (Maizels, 1977; Semiromi *et al.*, 2025). Infiltration closed depressions, which formed mainly on outwash surfaces through the melting of dead-ice blocks with relatively regular geometry, tends to preserve more symmetrical, circular forms.

Post-formational processes are also of considerable importance. Research by Juselius-Rajamäki, Välranta and Korhola (2023) demonstrates that peatlands in Finland can expand laterally at rates of up to 6.4 cm per year. Over longer timescales, peat accumulation promotes the gradual coalescence of adjacent

peat-filled depressions, leading to the development of larger areas dominated by evapotranspiration processes and extensive catchments. These processes are absent in CD_I , which helps explain their smaller size and shorter perimeters.

Differences in slope gradients may also be related to land use and land cover (LULC). The CD_E forms are more frequently utilised for agricultural purposes. As reported by Johnston (2013), many of these forms have been anthropogenically modified by infilling with soil to level the terrain and adapt it for agricultural use, further contributing to slope smoothing. In addition, Gillijns Poesen and Deckers (2005) indicate that cultivation-related erosion leads to progressive slope reduction. In contrast, CD_I , which are more commonly located in forested environments, experience limited erosional modification due to vegetation cover, which protects slopes and allows for a longer preservation of their original morphology.

Comparing morphometric parameters of CDs with those reported by other authors is challenging, primarily because of differences in delimitation methods. There is no consensus in the literature on where to draw the boundary between a CD and its catchment. In the case of CD_E , the boundary is usually defined relatively easily, based on the shoreline of a pond or the extent of a peatland (Major, 2008). Greater difficulties arise for CD_I , for example, Major (2009) defines them as concave landforms enclosed by a double contour line with an inward-pointing spur. Owing to the lack of a clear definition, some authors (eg. Gillijns Poesen and Deckers, 2005; Nowicka, 2016), as in the present study, treat the CD as the entire landform catchment.

Using the BDOT10k database rather than the more commonly used CORINE Land Cover 2018 (EEA, 2018) provided a much more detailed picture of LULC, particularly important given the small size of many CDs. CORINE Land Cover 2018 is based on generalisation typical of 1:100,000-scale maps, which is suitable for large-scale analyses but does not adequately capture small landscape features. The BDOT10k corresponds to 1:10,000-scale mapping accuracy and therefore allows the identification of finer landscape elements. For this reason, BDOT10k is frequently used in Poland for studies of catchments and buffer zones, as confirmed by previous research (Kutyla, Kolada and Ławniczak-Malińska, 2024).

Surface deposits primarily control LULC within CDs. In CD_I , forest and semi-natural cover predominates because these depressions are mainly situated on sandy substrates. Their low water and nutrient retention limits agricultural use (El-Akhdar *et al.*, 2024; Holanda de, Vargas and Granada, 2025). In contrast, CD_E are much more frequently associated with agricultural land, as they occur mainly on substrates where soils of good or very good agricultural quality develop, such as alluvial and clay soils (Parikh and James, 2012; Kabała, 2022).

The presence of ponds, small lakes, and wetlands within CDs means that part of the matter circulating within their catchments, including nutrients, does not enter the river system directly but is deposited or temporarily retained (Micun, 2014). Only during periods of increased catchment wetness, such as spring snowmelt or intense rainfall, may this material be released into the river network (Major, Pietruszyński and Cieśliński, 2021). As a result, CDs may help maintain the good ecological status of the Zbrzyca River, as confirmed in 2024 (GIOŚ, 2025). Unfortunately, due to climate change and anthropogenic activities, CDs, especially CD_E , are being degraded (Vasić *et al.*, 2020).

CONCLUSIONS

The results indicate that morphometric differences between infiltration closed depressions (CD_I) and evapotranspiration closed depressions (CD_E) are statistically significant; however, their effect size is small. This means that morphometric parameters alone do not provide a sufficient basis for unambiguous classification of, for example, depressions' hydrological types. At the same time, clear relationships were identified between CD s types and land use and land cover (LULC) structure. Evapotranspiration closed depression occurs more frequently in agricultural areas, whereas CD_I are mainly associated with forested environments. This suggests that anthropogenic factors largely shape the contemporary functioning of CD_E . The results confirm that closed depressions (CD s) should be regarded as complex geoeosystems, following the approach proposed by Major (2010), in which morphometry reflects their origin and development, while hydrological type influences their functioning within postglacial landscapes. Consequently, their analysis requires an integrative approach combining morphometric characteristics, hydrological context, and LULC conditions within the catchment.

From an applied perspective, the findings highlight the important role of CD s in landscape-scale water retention and in shaping environmental quality, particularly in agricultural landscapes. These forms may act as nutrient traps, provide habitats for a wide range of plant and animal species, often of conservation concern, and may also be incorporated into nature-based solutions supporting water retention and climate change mitigation. Therefore, they should be explicitly considered in spatial planning and water management strategies.

The observed relationships may also apply to other young glacial regions with similar environmental conditions; however, local factors such as land-use intensity or lithology may modify these conditions.

Accordingly, future research on CD s should focus on field-based verification of their hydrological functioning, including analyses of water balance and temporal variability, as well as the development of spatial analytical methods accounting for spatial autocorrelation. Expanding analyses to other regions would further enable a more robust assessment of the generality of the results.

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

DATA AVAILABILITY

A digital topographic map (1:10,000 scale) can be accessed via WMS services at <https://mapy.geoportal.gov.pl/wss/service/img/guest/TOPO/MapServer/WMSServer>, accessed on 12 November

2025. Other datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES

During the preparation of this work, the authors used Grammarly to proofread the text for correctness in language style, grammar, and punctuation. After using this tool, the authors reviewed and edited the content as necessary, taking full responsibility for the publication's content.

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