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# The morphogenesis of erosional valleys in the slopes of the Drwęca valley and the properties of their colluvial infills

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**Abstract.** The article characterises Late Glacial and Holocene deposits and provides a morphometric analysis of erosional and denudation valleys in the slope and terraces of the Drwęca Valley near Jajkowo village, a few kilometres east of Brodnica. A detailed field mapping was used to identify in detail two such forms within the western slope of the Drwęca Valley. Based on the results, it was found that the longitudinal profiles of these forms are not aligned (with an inclination of approximately 4°). The slopes of valley I are asymmetrical, with the southern slope being milder than the northern exposure, which is not the case with form II. Form I is narrower and has a V-shaped cross profile, while II is wider and has a trough-shaped profile cross profile. The side valleys were initially cut by the flow of what were most probably meltwaters and precipitation water from the moraine plateau, then the erosion stopped and the valleys gradually filled and widened mainly as a result of rinsing and mass movements, which may have been increased by man. Currently, forestry use is significantly reducing the activity of slope processes and rinsing. The sediments that fill the bottoms of these forms are usually consist of silt or sandy lithofacies with massive, streaky or deformation horizons. They are characterised by a significant enrichment in organic matter which is typical for colluvial deposits of young glacial areas. The relatively high pH values result from the investigated erosional forms intersecting into sediments rich in calcium carbonate. Moreover, groundwater flowing from the moraine plateau may also be the source of basic components.

**Key words:**
erosional and denudation valleys,
slope sediments,
slope processes,
colluvial/colluvial deposits,
Drwęca valley

## Introduction

The slopes of young glacial river valleys are an interesting place to observe denudation processes. These are expressed, among others, in numerous concave forms in the slopes (the valleys of small watercourses, erosional and denudation valleys, denudative troughs, permafrost niches, flat-bottomed valleys, young erosional cuttings. The evolution of studies on erosional and denudation slope forms was recently summarised by Paluszkiewicz (2016), who indicated at the same time that the main research problem was the genesis, evolution and classification of these forms. Their asymmetry was also a problem. Paluszkiewicz (2016) also pointed out where research had been conducted on the morphology, morphodynamics and morphogenesis of edge and morphogenetic zones (see Paluszkiewicz 2016). The slopes of the valleys, ice-marginal valleys, and the edges of outwashes have taken the interest of many researchers studying erosion and denudation, including soil erosion in both young glacial (Marsz 1964; Churska 1965, 1976, 1989; Kostrzewski 1971; Stochlak 1978; Nowaczyk 1991; Sinkiewicz 1994, 1998; Paluszkiewicz 2007, 2008, 2009, 2011, 2013, 2014, 2016; Smolska 2007, 2008; Majewski 2008, 2013; Tylmann 2011; Mazurek and Paluszkiewicz 2013; Paluszkiewicz and Ratajczak-Szczerba 2013, 2014; Jaworski and Juśkiewicz 2014; Ratajczak-Szczerba and Paluszkiewicz 2015; Świtoniak et. al 2015; Pindral and Świtoniak 2017) and Saalian glaciate areas (Klatkowa 1954, 1965, 1989a, b; Maruszczak 1968; Twardy 1995; Turkowska 1999; Jonczak and Kuczyńska 2008). Studies have excluded escarpment zones built of loess, which are prone to gully erosion and further evolution through anthropopressure (see Zgłobicki 2008).

The genesis of these forms is most often associated with the late glacial period but one must not forget their subsequent transformation by rinsing, erosion, mass movements, and even in many cases human activity (e.g. Churska 1965; Twardy 2000, 2003; Smolska 2007, 2008; Majewski 2008, 2013; Zgłobicki 2008; Paluszkiewicz 2011, 2014, 2016 and many others). Erosional and denudation forms have excellent potential for the reconstruction of erosion, sedimentation, climate and soil processes, and are an indicator of the rate and intensity of changes in land use. Dorywalski (1958) indicates that "erosion and soil denudation not only relate to changes in soil cover; they constitute what is certainly a more advanced process that leads to dynamic changes on the surface of the earth". In describing the Drwęca valley, Niewiarowski (1973) emphasised that the course of denudation processes on its slopes is influenced by a number of factors: land relief, geological structure, land use, and above all, water erosion. Recognising how these factors influence the evolution of erosional forms in the slopes of the Drwęca valley will help us better understand this valley's morphogenesis.

The main research problem undertaken in analysing the Drwęca Valley slopes and escarpment zone of the moraine plateau is to identify the mechanism that led to the formation of the concave erosional forms and assess the current dynamics of the processes shaping these forms. This required several more specific research objectives:

- identifying the structure, morphology and morphometry of the studied forms,
- identifying the morphogenetic processes that shaped the erosional marks,
- recognising and classifying the sediments within these forms (lithofacial characterisation of sediments),
- identifying the textural features of sediments,
- classifying the studied forms according to the typology of erosional and denudation valleys based on literature data,
- identifying the impact of climatic and habitat conditions on soil development within the studied forms,
- identifying the influence of human activity on morphogenetic processes within the escarpment zones of the case in hand.

## Research area

The study area is located within the Drwęca Valley mesoregion, which is adjacent to the Brodnica Lake District and the Chełmno Lake District to the north, to the Dobrzyń Lake District to the south and the Lubawa Hummock to the east (Kondracki 1998; Solon et al. 2018). Administratively, the area is in the Brodnica poviat in the north-west of the Kuyavian-Pomeranian Voivodeship. The land relief of the research area and its immediate surroundings is very diverse (Fig. 1). This area was covered by the most recent glaciation – the Weichselian – and has all the characteristics of a young glacial landscape. The last stage in shaping the topography of this area was during the ice sheet retreat in the Kuyavia-Dobrzyń subphase and during the stop and deglaciation of the Krajno-Wąbrzeźno subphase (Niewiarowski 1968, 1986). The valley slopes differ in height and morphology. Fragments adjacent to the moraine plateau have the smallest heights, ranging from 4 m to 15 m, they are strongly denuded and less diverse (Fig. 2). They are made of till deposits covered with denudation sediments (Niewiarowski and Wysota 2000). The slopes adjacent to the medium-height terraces reach a height of 20–30 m, and slopes adjacent to low terraces are strongly cut into by side valleys of up to 40–60 m deep. Their geological structure displays several exposure

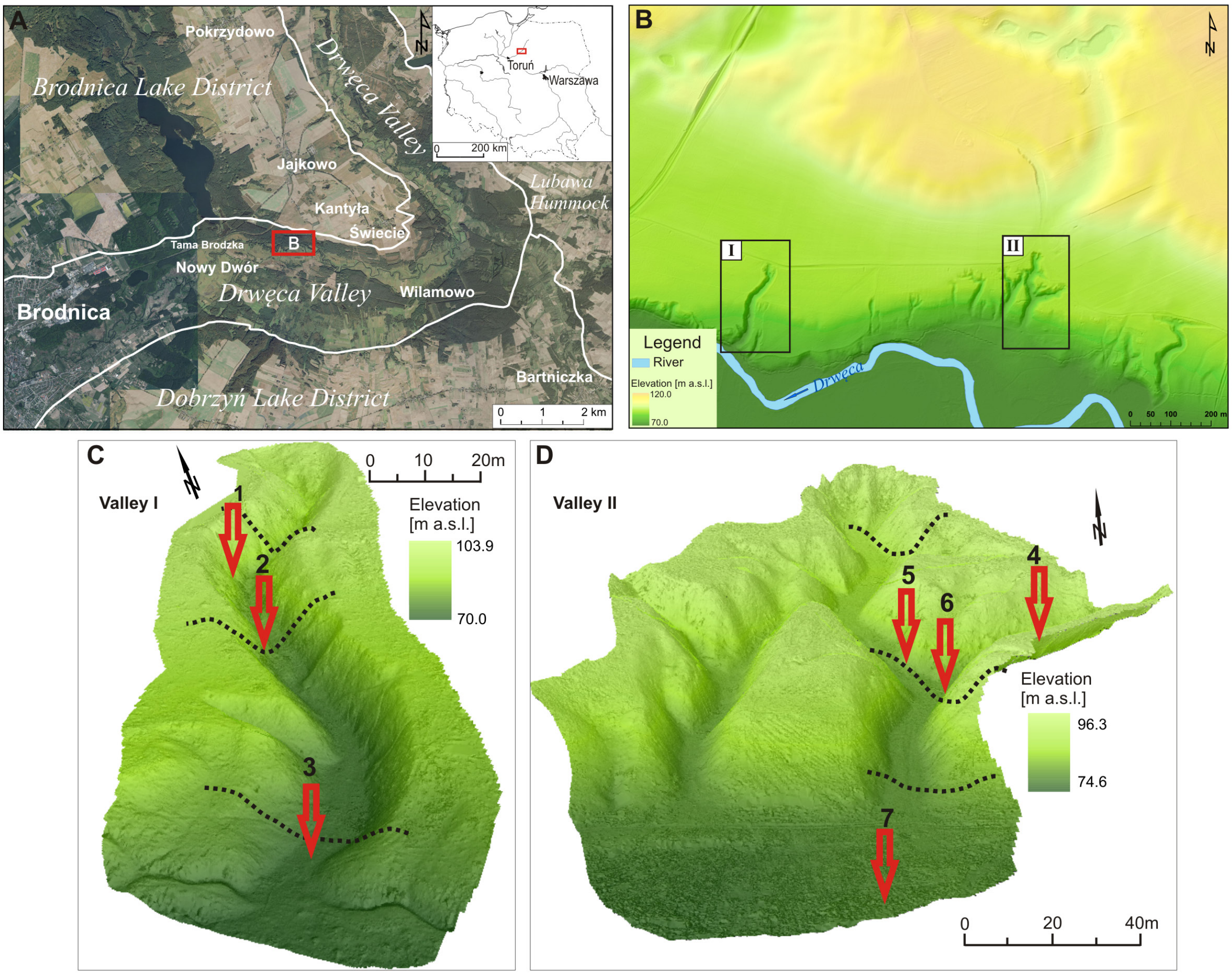



Fig 1. Location and relief of the study area; A – location of the study area against physical and geographical units according to Solon et al. 2018; B – Digital Terrain Model of study area; C and D – numerical terrain models of valleys I and II made on the basis of terrestrial laser scanning (TLS) with marked lines of transverse hypsometric profiles (dotted line) and places of excavations made (red arrows and number of pits)

of tills, and fluvioglacial and glacilacustrine sediments (Niewiarowski 1968, 1973).

The Drwęca Valley was initially formed by waters running from the melting icesheet which, as assumed by Niewiarowski (1968), flowed along the outwash routes. These streams merged into one bigger river in the area of the lower valley of Drwęca, which flowed into Toruń-Eberswalde ice-marginal valley. In the next stage, river waters led to the development of Drwęca's valley. Progressive lowering of the erosive base in Pleistocene caused the development of the several terraces (Niewiarowki, 1968). Quoted author drew also attention to the existence of older depressions that predisposed the develop-

Fig. 2. A part of the Brodnica Upland and the valleys of meltwater cutting it (photo M. Świtoniak)

ment of the Drwęca Valley. They were filled with ice-dammed lake or other limnic sediments.

## Methods

In order to meet the study's main objectives, field work, and laboratory and desk research were conducted. In the field, geomorphological mapping was performed, and 15 boreholes made with a manual auger of maximum depth of 4 m. The most information came from identifying the geological structure of sediments recognized in 7 pits of up to about 2 m deep (three pits in valley I and four in valley II – Fig. 1 ). In each of the boreholes, a lithofacial analysis of colluvial sediments and their substratum was performed. Textural and structural traits were determined using the Miall lithofacial code (1977) modified by Zieliński (1995) and Zieliński and Pisarska-Jamroży (2012). Eighty-seven sediment samples were collected for further laboratory analysis to determine the nature of individual horizons and their lithological boundaries.

The laboratory tests included:

- granulometric sediment analysis using a combined method (sieve and laser),

- determination of organic matter content (in %) by loss-on-ignition in a muffle furnace for 3 hours at 550˚C,

- determination of $CaCO_3$ content (in %) using a Scheibler apparatus (Bednarek et al., 2004),

- pH determination in destiled $H_2O$ by potentiometric method at a sediment–water ratio of 1:2.5 for mineral samples, 1:5 for mineral-organic samples and 1:10 for organic samples,

- determination of electrical conductivity (EC) by the conductometric method.

Most analyses were performed according to the methodology proposed by Bednarek et al. (2004) with the exception of the grain-size analysis, for which the procedure proposed by Mycielska-Dowgiałło (1995) was used. The percentage contents of individual fractions were calculated taking into account the grain-size scale according to Wentworth (after Mycielska-Dowgiałło 1995) and the parameters of the basic grain indices such as $Mz$, $\sigma_1$, $Sk_1$ and $K_G$ as proposed by Folk and Ward (1957) and expressed in the φ scale using Gradistat 8.0 software (Blott and Pye 2001).

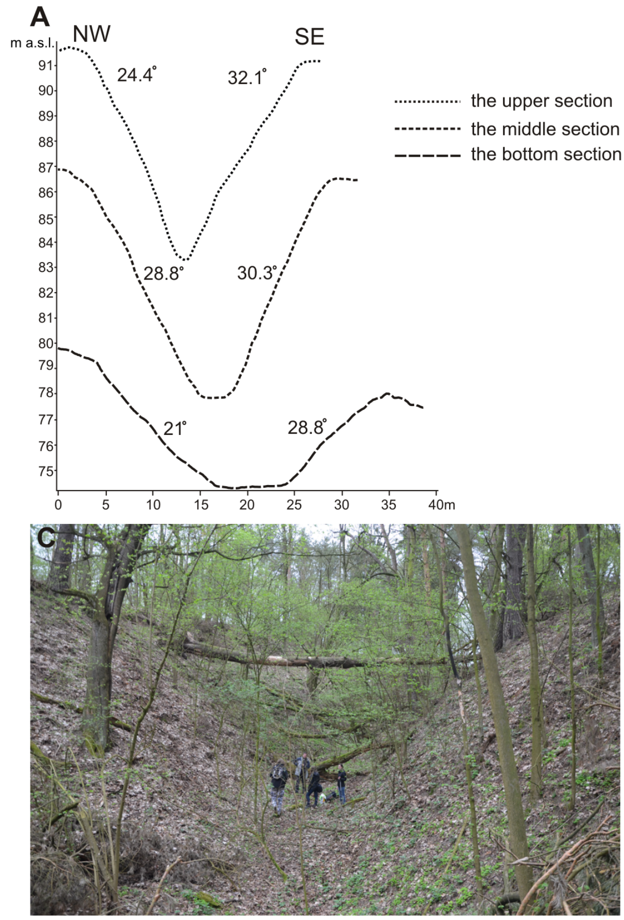
When making hypsometric profiles, terrain models made using LiDAR data and data from terrestrial laser scanning were also used (Fig. 1). A Riegl VZ-4000 terrestrial laser scanner was used to image the contemporary land relief and morphology. It was used to obtain data from 6 sites that were located on both sides of the valleys (valley I – 18 sites; valley II – 14) in such a way as to eliminate the possibility of measurement shadows. Measurements were made at a resolution of 0.04–0.06°. Then the point clouds were combined using the *Multi Station Adjustment* module and filtered to obtain only reflections coming from the ground. The average density of the final point cloud was 650 pts/$m^2$. The resultant data was used to create a high-resolution raster terrain model with a pixel size of 5 cm.

The following programs were used in preparing the drawings: Microsoft Excel 2003 for calculations and ArcGIS 9.3 and CorelDraw X4 for graphics.

## Results

### Morphometric valley characteristics

Valley I is located in the west of the research area (Fig. 1). It cuts into terraces X, III and II of the Drwęca (Niewiarowski 1968). Its source area has a dendritic layout, and the edge of the upper escarpment is quite sharp. It is worth adding that this arrangement indicates erosion processes were inhibited by vegetation, as indicated by Marsz (1964). Just beyond its source area, the valley runs south-westwards. It changes direction to the south-east in the middle section (Fig. 3), and in the lower section it goes south-westwards again. Its course is nearly straight. At the mouth, the alluvial fan has not been preserved, and was probably removed by the waters of the Drwęca River undercutting the valley slope. Within the analysed valley, one branch that is poorly marked on the map can be distinguished; it is short (35 m) and shallow (about 3 m), indicating that it is young. The main valley is 250 m long and its longitudinal profile is uneven, with an average slope of 4.2° (Figs 1 and 3). The height



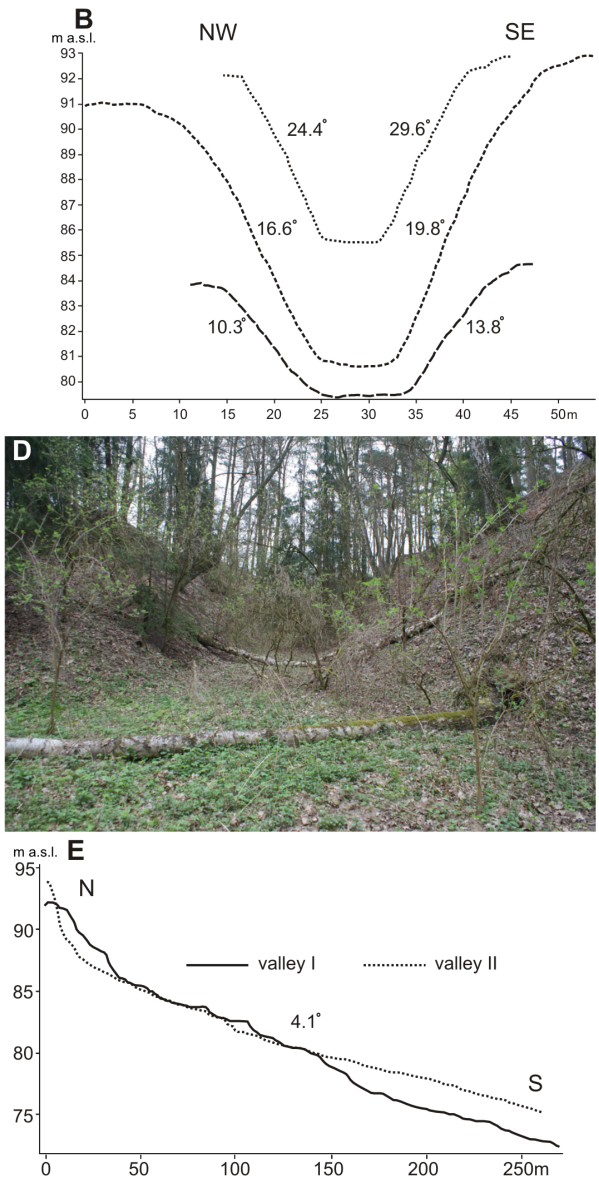




Fig 3. Erosion and denudation valleys; A – hypsometric profiles through valley I; B – hypsometric profiles through valley II; C – the middle part of the valley I, D – the middle part of the valley II; E – hypsometric profiles along the bottom of both valleys

difference between the upper and lower section is approx. 19 m.

Valley II is located in the east of the research area (Fig. 1) and cuts into the same terraces as Valley I, but it is a more branching form. The analysis was performed on its main, western branch (Fig. 1). Among the numerous secondary slope forms, the largest and longest branch is on the eastern side, and its mouth is halfway along the main valley (Fig. 1). This side valley has a length of 80 m and is cut to a depth of 3–4 m in the upper section, 5–6 in the middle and 6–10 m in the bottom. The source area of the valley has a dendritic outline. The main valley is about 220 m long and at its mouth a fan extending about 100 m and the morphological thickness of the fan about 1 m has formed in the bottom of the Drwęca valley. The longitudinal profile of this valley is even, and inclined at about 4° (Fig. 3). The height difference between the upper and lower section is approx. 17 m.

## Valley fill sediment characteristics

In order to identify the sediment infill in valley I, three pits were cut, from which the sediment samples were taken for further investigations, taking into account the individual horizons (Fig. 4).

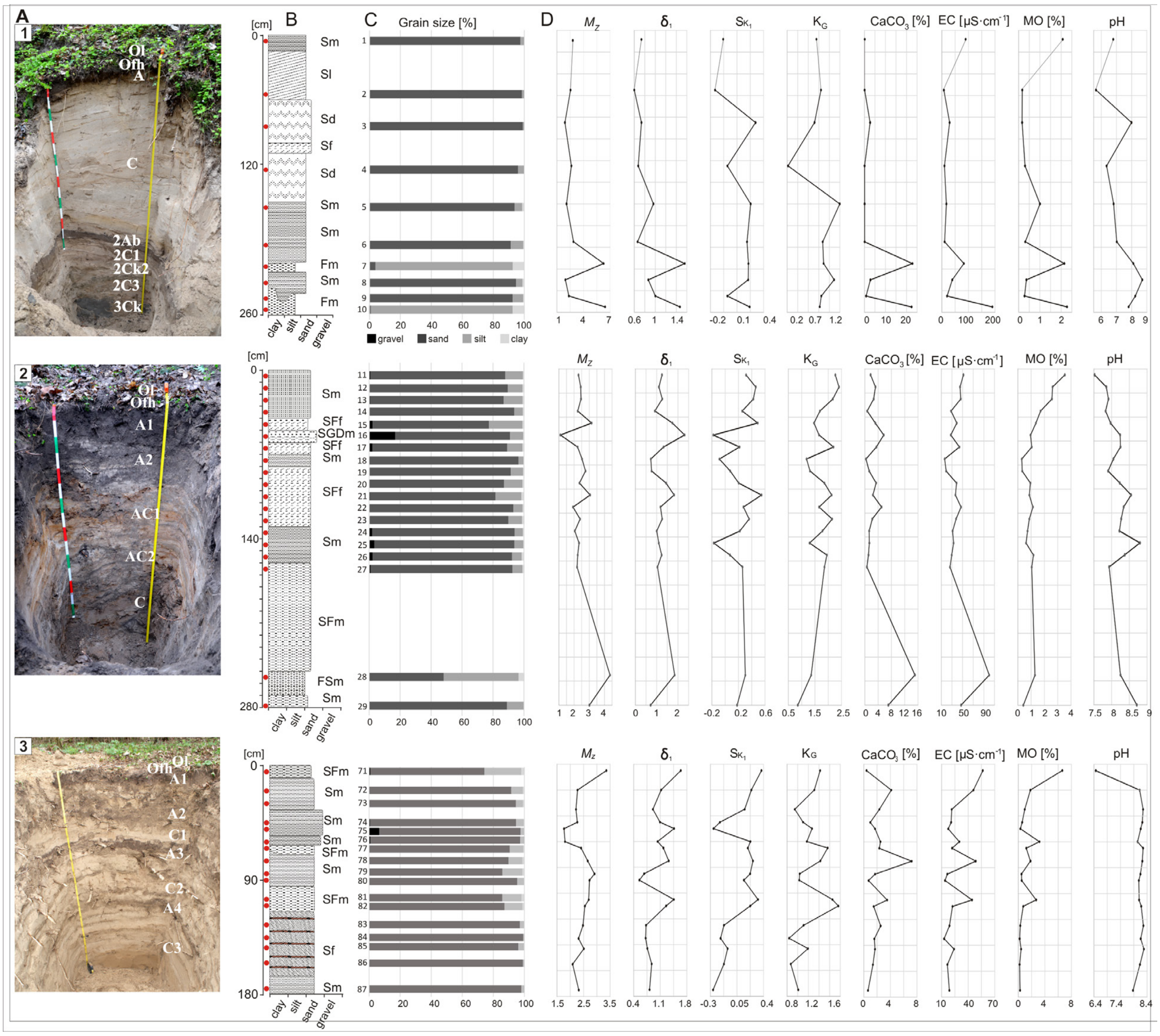



Fig 4. Valley I. Lithofacial profiles and percent content of basic fractions in the deposits, grain-size distribution indexes, CaCO3 content, electrolytic conductivity (EC), organic matter (MO) and reaction (pH) of the tested sediments (red dots with LOG profiles indicate the place of sampling for laboratory analyzes)

In the first pit (1), which was in the upper part of the valley, sediments were identified to a depth of 2.6 m. In the bottom of the series, the substratum deposits are clays and glacilacustrine silts that have an average diameter of 6.3–6.4 φ, are poorly sorted and have positive skewness, which along with poor sorting indicates a colluvial sedimentary environment with variable dynamics and without the influence of flowing water. They have high $CaCO_3$ content, are alkaline and have a very high EC level of 200 $\mu S \cdot cm^{-1}$.

Colluvial deposits are present in the middle of the profile at a depth of between 2.12 and 1.58 m. They are formed of varigrained sands with massive structure, and are moderately well-sorted with positive skewness. They have extremely variable $CaCO_3$ contents, pH between 7 and 8.5, higher EC and elevated organic matter content relative to the underlying sediments, particularly in horizon 7 (2Ab).

In the upper part, from a depth of 1.58 m there is a series of medium-grained and fine-grained sands of disturbed structure (*Sd, Sf*). This horizon has clearly interbedding of rust, indicating the movement of iron compounds. These sediments are moderately well-sorted, with negative skewness (Fig. 4), and are free of calcium carbonate with variable reaction – with pH between 5.5 and 8. They also stand out for their very low EC and, apart from the current surface humus level (0–10 cm), are almost devoid of organic matter. The fact that these sediments were deposited on a series of colluvial sediments, preserved, undisturbed stratification *Sl* and lack of OM indicate they originate from landslides. According to the Polish Soil Classification, this profile is of weakly developed sandy soil – i.e. arenosol. According to the WRB (IUSS Working Group WRB 2015), the soil formed by these sediments was classified as Dystric Arenosol (Ochric).

The second pit was located in the middle section of the valley (Fig. 4, pit 2) to a depth of 1.7 m, which was further deepened to 2.8 m with a manual auger. The colluvial sediments are thickest in this part of the valley bottom, at approximately 2.7 m. They are characterised by the mixing of sands and varigrained silts. The average diameters range from 1 to 3 φ, which indicates fine-grained and medium-grained sediments (Fig. 4). The highest value of this index is for the sample taken from the sandy silt horizon (from a depth of 2.55 m it is 4.4 φ). The sediments are poorly sorted, and moderately in some places. In the lithodynamic interpretation "poorly sorted" may indicate a zone of washing (rozmywanie osadów). For most sediments, the skewness of grain-size distribution is very positive or symmetrical (at a depth of 0.7–0.9 m).

Massive transit prevails in the investigated deposits, and this is apparent from a positive skewness value. Additionally, the SM and SFm lithofacies alternate with sand-silt layers with flaser lamination (*SFf*) and massive sand-gravel diamicton (*SGDm*).

Individual horizons have different colours ranging from light to dark grey, which is associated with a variable content of organic matter (humus). The horizon at a depth of 2.7 m to 2.8 cm was considered to be the substratum sediments (terraced sands). According to the WRB classification (IUSS Working Group WRB 2015), the soil in the profile is a Haplic Phaeozem (Arenic, Colluvic, Pachic). According to the Polish Soil Classification (2011), it is a humic colluvial soil (Świtoniak et al. 2016).

In the mouth section of the valley, a pit (Fig 4; pit 3) was excavated to a depth of 1.8 m, where it the depth of colluvial sediments was found to be 1.65 m. The sediments in this part of the valley are mostly fine-grained sands. Only at a depth of 0.62–0.35 m do medium-grain sands dominate with a small amount of fine gravel (up to 6%). A high content of coarse silt was found in the surface horizon. Median grain diametr (Mz) of these sediments range from 1.8 to 3, .4 phi, and their sorting is weak and very weak (Figure 4), which indicates the high dynamics of the deposit environment (Racinowski et al., 2001). The structural and textural features of sediments in the bottom of the valley indicates three stages of their deposition (Fig. 4), which is expressed in horizons enriched with organic matter. In the lower part there are massive sands (*Sm*) and sands with flaser lamination (*Sf*) without organic matter. In the central part of the excavation dominate the massive sands and massive silt-sand deposits (*SFm* and *Sm*) separated by the humic horizons. In the upper zone of the series, similar gray deposits with a high content of organic matter were found. These are probably buried horizons of humic soils. During their development, denudation processes were inhibited. As with the previous pit, the soil is a humic colluvial soil (Polish Soil Classification 2011), and a Haplic Phaeozem (Arenic, Colluvic) according to the WRB (IUSS Working Group WRB 2015).

Within the second valley, four pits were excavated, including one on the alluvial fan at its mouth. In the upper escarpment of eastern side valley, a pit was excavated to a depth of 1.4 m, in order to identify the sediments forming the terraces in which the studied erosional form was formed (Fig. 5; pit 4). Medium-grained and fine-grained sands with massive structure (*Sm*) dominate here to constitute a typical rusty soil (Polish Soil Classification 2011) that is referred to as a Dystric Brunic Arenosol (Ochric) according to the WRB system (IUSS Working Group WRB 2015). No colluvia were found here. The bottom part is made up of very fine-grained sands and fine-grained sands with significant participation of medium-grained sands (up to 48%). In the central and upper part of the sediments in the profile, the share of medium-grained sands predominates. *Mz* values slightly increase from the top down to the bottom and range between 1.5 and 2.1 φ, with sediments becoming finer with depth (Fig. 5). They are moderately sorted, and their skewness is symmetrical (in the top and bottom sediments) and very positive (bottom sediments). They are acidic (pH from 4.6 to 5.2), except for the upper part, which is devoid of organic

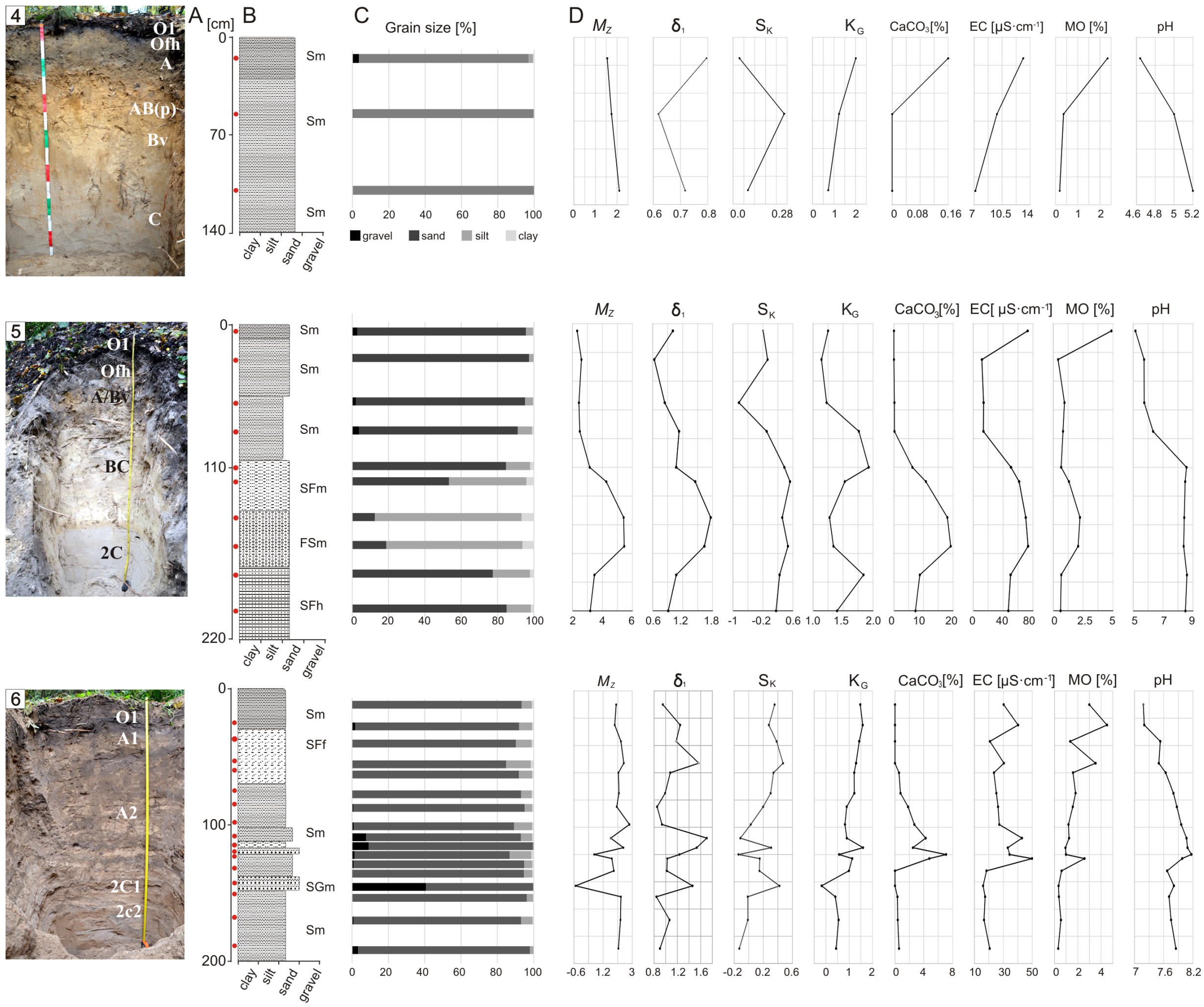



Fig 5. Valley II. Lithofacial profiles and percent content of basic fractions in the deposits, grain-size distribution indexes, CaCO3 content, electrolytic conductivity (EC), organic matter (MO) and reaction (pH) of the tested sediments (red dots with LOG profiles indicate the place of sampling for laboratory analyzes)

matter and carbonates and has a very low EC value (from 7 to 13 μS·cm$^{-1}$).

In the middle section of the valley, a pit was made to identify the geological structure to a depth of 2.2 m. It was found that below 1.7 m there are horizontally layered silty sands (*SFh*) that constitute the substratum of the colluvial sediments (Fig. 5, pit 5). Colluvia exposed in the upper part of the profile are formed (*Sm, FSm* and *SFm*) as fine- and very fine-grained massive sands (69–78%) and massive sandy silts (silts represent from 23 to 31%). From a depth of 1.7 m to 1.0 m the shares of the silty fraction (54–87%) and the clayey fraction (4.5–7.5%) increase. In turn, from 1.0 m to the top, the fine-grained fraction has the markedly dominant share. In sub-colluvial sediments at a depth of 2.0 m, *Mz* is 3.2 φ, then increases up to 5.5 φ in the upper part, and then drops to 2.3 φ in the surface sediments. The sorting of sediments is weak or moderate throughout the entire tested profile. The skewness distribution of the values is very positive in the bottom part (substratum deposits), then symmetrical (to a depth of 1.0 m), and negative in the top. Poor sorting of sediments in the lover section indicates the changes of dynamics of the deposit environment. Nevertheless, the flow energy could be large, causing redeposition or transit of sediments. Better sorting was found in surface sediments, which can be related to the stabilization of the deposit environment. At a depth between 1.1 and 1.6 m, $CaCO_3$ is enriched, with a clear increase of up to even 19%. At this depth, an increase in EC was also noted, with values ranging from 50 to 73.5 $\mu S \cdot cm^{-1}$. The reaction of the sediments at a depth of 0.8 m is slightly acidic, and alkaline deeper down (Fig. 5). In the colluvial material of the upper part of the exposure, mixed material from the genetic sideric horizon has survived, allowing the pedon to be classified as a typical rusty soil (Polish Soil Classification 2011) and as an Epidystric, Brunic Arenosol (Protocalcic, Colluvic, Ochric),

In the lower section of the valley II, an excavation was made (Fig. 5, pit 6), where it was found that colluvial sediments occur to a depth of 1.5 m, with massive, sandy substratum sediments (*Sm*) below them (down to 2 m). The colluvia are very well-mixed. This situation was previously described by Twardy (2008), who drew attention to the "rhythmicity" of the colluvia, which results from the occurrence of alternating sediments of two fractions - colluvial sands and sandy silts with massive structure or flaser lamination (*Sm, SFf*). In sediments at a depth of 1.5 to 1.0 m, alongside the sand fractions there are admixtures of gravel constituting up to 40% of the total sample (*SGm*). These may be proluvia (Stochlak 1978; Twardy 2000; Paluszkiewicz 2014, 2016). From a depth of 1.0 m to the top, the valley bed is made up of sandy-silt deposits with a large proportion of very fine-grained and medium-grained sands, and coarse-grained and medium-grained silts. In the majority of the tested samples *Mz* ranges from 1.7 to 2.8 φ (Fig. 5). The lower values are only for two samples with the gravel material from a depth of 1.2 m (0.6 φ) and 1.42 m (-0.5 φ). The distribution skewness is positive or very positive, indicates the delivery of a small fraction. For silty deposits in the bottom, the distribution of sorting becomes symmetrical (at a depth of 2.0–1.5 m) and negative (1.43 m). Higher values of $K_G$, confirm the stability of the deposit environment, the lower - the pulsatile changes in its energy. The soil was classified as humic colluvial (Polish Soil Classification 2011). According to the WRB classification (IUSS Working Group WRB 2015) it was a Haplic Phaeozem (Arenic, Colluvic, Pachic).

An excavation was made in the alluvial fan that accumulated at the mouth of the valley, and colluvial sediments were found to reach a thickness of 1.25 m (Fig. 6, pit 7). They are in the form of sands (up to a depth of 0.8 m, *Sm* or *Sh*), as well as silty sands and massive silts (1.0–1.1 m), which are enriched with organic matter and calcium carbonate, and have an elevated EC value (*SFm, Sm, Fm* and *FSCm*). Under the series of fan sediments, fluvial sediments were found in the form of silts enriched with organic matter (warps). And at a depth of 1.25 to 1.44 m, silt fractions prevail. These horizons are separated by a horizon of medium-grained, fine-grained and very fine-grained sands with the participation of mainly coarse- and medium-grained silts. It is worth noting that the sediments become finer from the surface down to the bottom, as also indicated by Tylman (2011), Paluszkiewicz (2008) and others in their observations. As in previous cases, the soil was classified as humic colluvial soil (Polish Soil Classification 2011) and a Haplic Phaeozem (Arenic, Colluvic, Endogleyic) in the WRB system (IUSS Working Group WRB 2015).

In order to analyse selected features of the sedimentary environment of the studied deposits, graphs of the mutual relations between the calculated grain-size indices $Mz - \delta_1$, $S_K - \delta_1$ were used

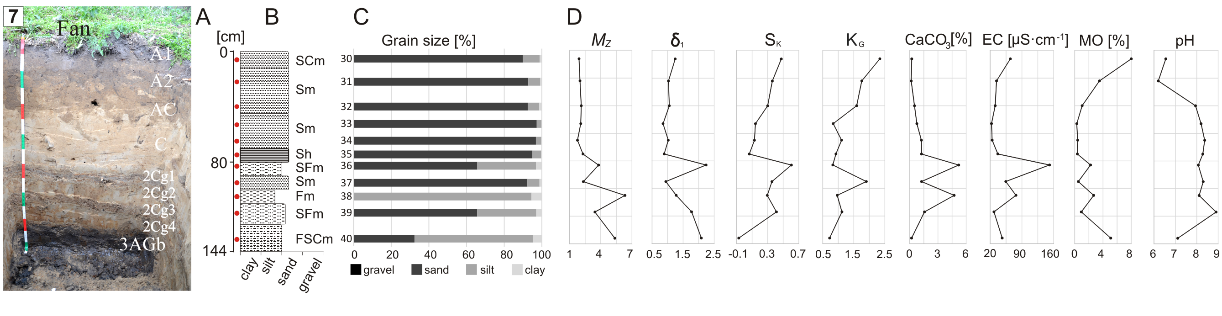



Fig 6. Cone at the mouth of the valley II. Lithofacial profiles and percent content of basic fractions in the deposits, grain-size distribution indexes, CaCO3 content, electrolytic conductivity (EC), organic matter (MO) and reaction (pH) of the tested sediments (red dots with LOG profiles indicate the place of sampling for laboratory analyzes)

(Folk and Ward 1957, Fig. 7). The graphs of the relationships were compiled separately for sediments from valley I and valley II, and for the fan at the mouth of valley II. Valley I deposits are the more homogeneous of the two valleys. In general, the sorting effect is lower with the increase in the average diameter of the grain. Mycielska-Dowgiałło (1995) states that this is typical for sedimentary environments with varied dynamics and significant variability of the transporting power of the sediment. Such dependencies were also confirmed, among others,by Twardy (2000, 2003) and Paluszkiewicz (2016). Against this background, the sediments deposited on the colluvial fan stand out. From the diagram (Fig. 7) we can conclude that the samples taken from the cone are better sorted, because their transport path was theoretically the longest. This relationship can be weakly seen in the samples taken from the upper and middle parts of the valleys.

In addition, cumulative curves analysis was used to determine the dynamics of the depositional environment of the sediments. Large part of samples reveals a similar shape of cumulative curves with a distinctive and steep saltation population that truncates between 1.0 and 4.0 phi (Fig. 8). This set additionally owes a flattish traction population along with a suspension part. Other samples as for example the 6th, 8th, 11th, 40th, 48th and 48th clearly show gently-inclined population of saltation, and thus meaning that sorting has a lower value comparing with the rest samples. Additionally, no traction population is present in this set, and suspension population is rather vague. Finally, the 59th sample looks odd, and not revealing clear populations (Fig. 8).

In the upper parts of the valleys, the flow rate and the load on surface waters was much higher, as evidenced by the thickness of washed layers, devoid of organic matter. In the middle and lower part of the valley the layers rich in OM are definitely thicker. A detailed analysis of the cumulative curves of the sediments making up the bottom of the lower and upper sections of the valleys indicates some differences in their shape, though these are subtle (Fig. 8). Basically, they confirm that the colluvia

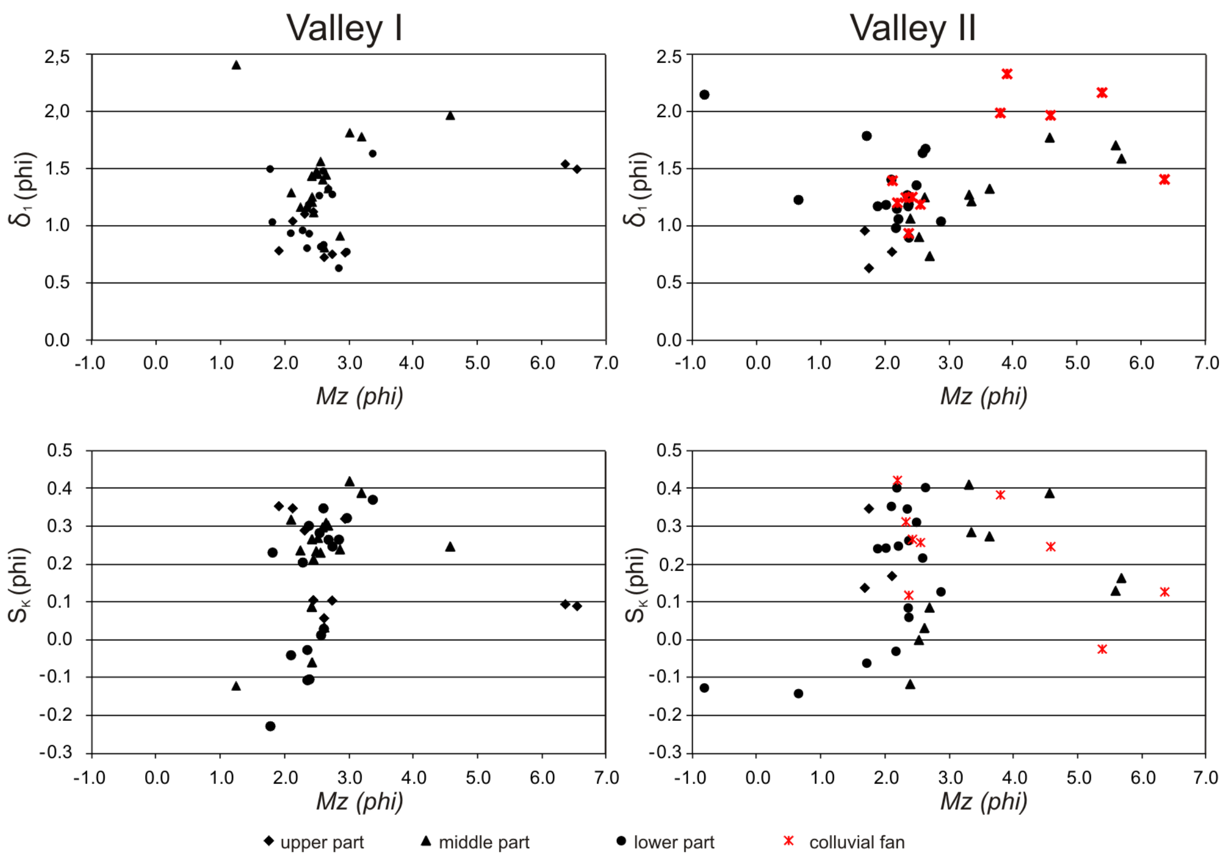



Fig 7. Relationships between grain-size distribution indexes: average grain diameter (Mz), sorting (δ1), average grain diameter (Mz) and skewness (SK)

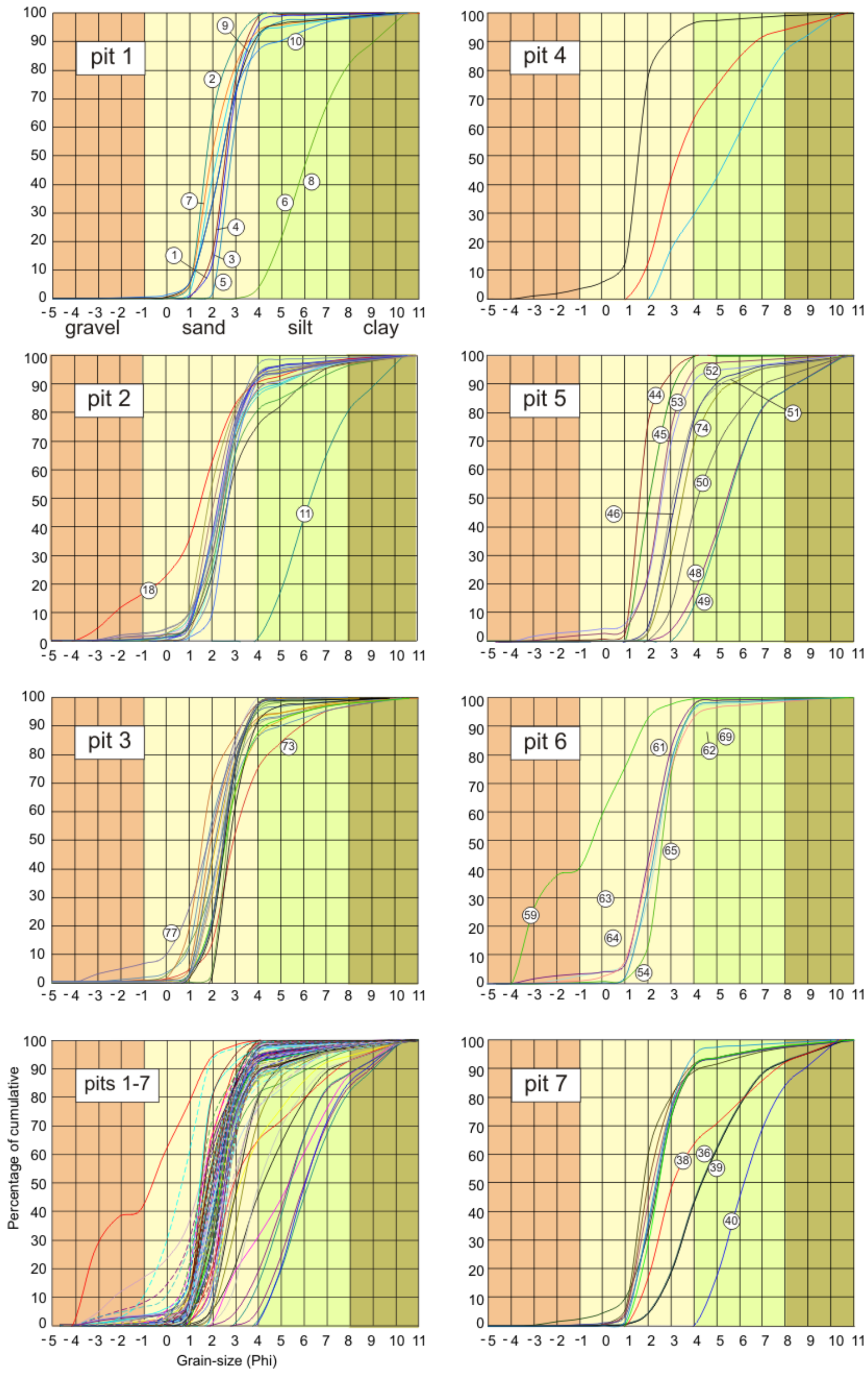



Fig 8. Cumulative curves for deposit samples from tested valleys (pits 1,2,3 from valley I, pits 4,5,6, and 7 from valley II)

are fine-grained, occasionally with a significant silt fraction. Some sediment samples are enriched with fractions of fine gravels. The dynamics of the environment were more moderate than high, which is largely indicated by the commonality of shape of the cumulative curves. Similarly, as Paluszkiewicz notes (2014, 2016), in the lower, middle and upper sections of the valley the formation of the upper part of the curve is visibly weaker, which according to Vischer's analysis (1969) indicates a small share of grain transport in suspension or by aeolian transport.

## Discussion

The analysed erosional and denudation valleys in the slope of the Drwęca valley probably were shaped during the late glacial period under periglacial climate conditions. These forms are found in the prolongation of tunnel valleys and valleys that drained southern parts of the Brodnicki Lake District as lumps of dead ice filling in thaw depressions degraded. According to previous research, this process took place mainly in the Oldest Dryas, as indicated by, *inter alia* Churska (1965), Maruszczak (1968), Marsz (1964), Majewski (2008) and Tylman (2011). As claimed by Tylman (2011), waters from a higher area flowing over the frozen ground heat up the ground and melt frozen sediments. And this causes the initial downcutting and begins the development of valleys. The edge zone also comes into play, where the flow accelerates and increases downcutting. The climate of both the Late Glacial and the Holocene were characterised by thermal and moisture fluctuations. In warmer periods, erosion processes dominated, especially when there was not yet a dense vegetation cover. Then it was flushed and sand deposits with a massive structure (*Sm*) or silty-sandy deposits (*SFm*), were accumulated without any admixture of OM. Majewski (2002) believes that permafrost hindered infiltration and thus increased erosion. In addition to erosion, there are also rinsing and solifluction – processes that cause slopes to retreat and valleys to widen. And if linear erosion can not keep up with the removal of slope sediments, this also leads to they infilling and shallowing of valleys (Majewski 2008; Tylman 2011; Paluszkiewicz 2009, 2011, 2014, 2016). Nearby paleogeographic studies (Karasiewicz et al. 2012, 2014) indicate that the Allerød was a warmer period in this area and a dense vegetation appeared, which may have significantly inhibited erosion. Then the soil cover was developed, the traces of which are visible in sediments that fill up the valleys, eg in sediment digs 2 and 6. Alternate deposition of sandy and silt deposits without OM and containing OM is visible on EC diagrams (Figs 4, 5 and 6). Diagrams with a higher EC value have greater overall mineralization. Sediments containing higher amounts of OM are generally characterized by higher pH values due to the presence of humins.

In the Younger Dryas, a cooler period, the vegetation cover may have thinned out again (Noryśkiewicz 2012) and rinsing again became more significant. Other researchers have also indicated this type of relationship (Paluszkiewicz 2009, 2011, 2014, 2016; Tylman 2011; Majewski 2013). During the Holocene, the analysed valleys were only slightly transformed by rinsing (water erosion), denudation and mass movements. In one of the studied forms (valley II), there were horizons of sediments indicating human activity, so in the later period this may have influenced their shaping through, for example, a change in land use (burning, deforestation).

## Conclusions

To sum up: the valleys were initially deeply downcut and later filled with colluvial sediments. Based on the data, it can be concluded that the examined valleys may have been initially deeper than they are today, by even three metres. The poor and moderate sorting of colluvial sediments indicates short-distance transport of sediments in their bottoms.

The colluvia of individual parts of the analysed forms was determined to of variable thickness. The maximum thickness of the colluvia is 2.7 m. Structural and textural studies identified the main lithological features of the colluvia and substratum sediments. *Inter alia*, it was found that:

1) the substratum sediments developed as varigrained terraced sands with admixture of grav-

els, and as clays and silts. The main lithofacies representing substratum deposits were: Sm, SFh and FSCm.

2) colluvial sediments of varying thickness represented mainly by: fine-grained sands; silty sands; and silts of massive, streaky or disturbed structure. The calculated indices of grain-size and physicochemical properties of colluvial sediments and substratum sediments allowed them to be characterised and differences between them to be revealed:

- the average diameter of colluvial sediments ranged from -0.50 to 6.33 φ, and from 1.54 to 6.44φ for substratum sediments;

- the colluvial sediments are more poorly or similarly sorted compared to the substratum deposits, the colluvial sediments being poorly or moderately sorted;

- skewness values for the colluvial sediments are variable and distributions range from positive to negative, and for sediments of the substratum the skewness of sediments is positive or symmetrical;

- the reaction of sediments increase from the surface downwards, from acidic to alkaline; the surface acidity of the sediments can be explained by the presence of soil humus acids;

- electrical conductivity was greater for horizons with a fine fraction (sandy-silty, silty) that was very uniform within the colluvia;

- the higher content of organic matter indicated the onset of soil processes in the horizons covered by colluvial sediments and thus the dynamics of denudation processes;

- the calcium carbonate content increased in places rich in the clayey and silty fraction typical of colluvial sediments and also for substratum sediments formed as silts and glacilacustrine clays.

## Disclosure statement

No potential conflict of interest was reported by the authors.

## Author Contributions

Study design T.K. L.T.; data collection T.K., L.T, M.Ś., K.M., S.T.; statistical analysis T.K.; result interpretation T.K., L.T., M.Ś; manuscript preparation T.K., L.T.; literature review: T.K., L.T., M.Ś.

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