

Development of gullies and sediment fans in last-glacial areas on the example of the Suwałki Lakeland (NE Poland)

Ewa Smolska

Warsaw University, Faculty of Geography and Regional Studies, Krakowskie Przedmieście St., 30, 00-927 Warszawa, Poland

Accepted 1 August 2006

Abstract

The density of gully network in the Suwałki Lakeland (northeastern Poland) with typical last-glaciation relief is 0.2 km/km^2 on average and locally reaches 1.2 km/km^2 . Most gullies are isolated but sporadically they create dendritic patterns. The larger gullies are developed along dellies (bowl-shaped, dry valleys) or melt-out valleys. The smaller and shorter gullies occur on the slopes of melt-out depressions and tunnel valleys. Ages of peat covered by fans at the mouths of larger gullies indicate that gully erosion started between 3520 ± 70 to 2240 ± 100 BP. Two different units build the fans and infilled the gullies. The older unit in the lower part of fans is up to 5 m thick, contains sand and gravel that generally originated from the bottom and bank erosion of the gullies and resembles alluvium. The younger unit, about 2–3 m thick, consists of colluvium. The fans at the mouths of smaller and shorter gullies are mainly built of colluvium. The maximal grain diameter in both units is similar, which testifies to a similar intensity of extreme rainfalls. The analysed sediments have different characteristics, which indicate that the source material and depositional changes are linked to forest clearance and farmland expansion starting in the 7th century AD and continuing in the Middle Ages.

© 2006 Elsevier B.V. All rights reserved.

Keywords: Gully erosion; Gully development; Fan sediment; Late Holocene; NE Poland

1. Introduction

The majority of studies focusing on gully formation shows that their origin is usually triggered by forest clearance and development of agriculture (Bork, 1989; Bork et al., 1998; Lang and Höhnscheidt, 1999; Lang, 2003; Dotterweich et al., 2003; Sidorchuk and Golosov, 2003; Stankoviansky, 2003). Such an opinion is also shared by many Polish researchers (Maruszczak, 1986; Klimek, 1988; Burczyński, 1989/1990; Maruszczak, 1991; Sinkiewicz, 1994; Twardy, 1995; Sinkiewicz, 1998; Klimek, 2002, 2003; Zgłobicki et al., 2003; Twardy, 2005; Starkel, 2005), however detailed studies focusing on singular landforms sometimes allow for different conclusions (Kalicki, 1996; Kalicki et al., 2004; Belyaev et al., 2004, 2005; Smolska, 2005). Dense forest cover and lack of archaeological sites in an area usually discourage scientific studies. Former landscape can be reconstructed if colluvial and alluvial sediments linked to soil erosion are

analysed (Bork, 1989; Śnieszko, 1995; Bork et al., 1998; Twardy, 2002; Klimek, 2002, 2003; Dotterweich et al., 2003; Belyaev et al., 2004; Dotterweich, 2005). The mechanism and development conditions of the gully erosion are discussed by Poesen et al. (2003), who emphasize the role of local factors which can markedly modify general trends in the development of the fluvial landforms linked to global climatic changes. Differentiating between a climatic factor and human influence on landforms is very difficult in inhabited areas. The phases of erosion are usually correlated with the phases of settlement, and climatic conditions are thought to be less important in the development of small fluvial landforms (Klimek, 2002; Twardy, 2002; Klimek, 2003; Dotterweich et al., 2003; Lang, 2003; Zgłobicki et al., 2003; Zolitschka et al., 2003).

The Suwałki Lakeland (northeastern Poland) was cultivated only to a limited degree. The differential morphology of gullies encourages a detailed study of their development. The aim of this study was to determine the phases of gully erosion in reference to the settlement history of the area. Particular

E-mail address: e.smolska@uw.edu.pl.

focus was paid to sediments linked to gully erosion and their characteristics showing the course of the process.

2. Study area

The study area is located in northeastern Poland within the Weichselian Glaciation range (Fig. 1). The landscape is typical of last-glacial surfaces with altitudes between 145 and 280 m a.s.l. Several tunnel valleys and vast glacial depressions (about 1 km wide) filled with dead ice at the end of the glacial recession (Ber, 2000) mark the area. These forms have maximum slope lengths of 100–150 m and heights of 50–70 m. Locally, the slopes are dissected by dellies and gullies. The average density of the gully network in the Suwałki Lakeland is 0.02 km km^{-2} (Józefaciuk, 1991).

The climate of the study area is temperate continental (Stopa-Boryczka and Martyn, 1986) with mean annual air temperature of $6.1 \text{ }^\circ\text{C}$ and average precipitation of 635 mm, varying between 464 mm and 783 mm annually.

Cultivation of land and pasturing began with the arrival of the Balts, about the middle of the 8th century BC (Brzozowski et al., 1993). Forest clearance proceeded very slowly. Based on pollen analysis of cereals and grasses found in lacustrine sediments and peat, it is estimated that in the early Subatlantic period, the forest cover was destroyed on 5 to 7% of the area (Stasiak, 1971). Settlements were separated from each other by a dense forest cover. Dynamic settlement started with the development of the Jadwings culture and then, the Jadwings state. Last settlement phase is linked to the arrival of people from Masovia in the 15th and 16th AD.

Today, forest occupies 27% of the area. Due to a high proportion of steep slopes and many internal drainage basins, meadows and pasture land occupy 15% of the area while

arable land occupies about 43% of the area. Numerous lakes constitute almost 8% of the area.

3. Methods

The morphometry of the gullies was analysed in 3 selected areas (Fig. 1) based on topographic maps 1:10 000. Long profiles and cross sections of selected gullies were determined with the use of GPS. 25 gullies were measured (10 in the vicinity of Stańczyki, 10 near Gulbieniszki and Udziejek and 5 near Prudziszki). An especially large number of cross sections (from 7 to 10) was obtained for each of the selected 6 gullies (Fig. 1) in order to calculate their volume according to the method of Klimczak (1988). The volume of fans deposited at mouths of the 6 gullies was calculated using the same method (3–4 cross sections for each fan). Thickness of fan sediments was determined by a hand drill. Usually 3 drillings were done on each fan: the first in a fan's proximal part (near a mouth of a gully), the second in its middle part and the third in its distal part. Buried peat horizons or coarse fluvio-glacial sand and gravel were assumed to be the fans' substrata.

Sediment infill of the gullies as well as sediments of the fans were analysed in pits and shallow drillings. Samples for granulometric analysis were taken from several pits and drill-cores which first underwent macroscopic examination. Granulometry was determined with use of sieves and hydrometer. Granulometric indices: mean grain diameter, standard deviation and skewness were calculated according to the graphic formulae provided by Folk and Ward (1957).

Organic content was determined by loss on ignition in fraction $<1 \text{ mm}$.

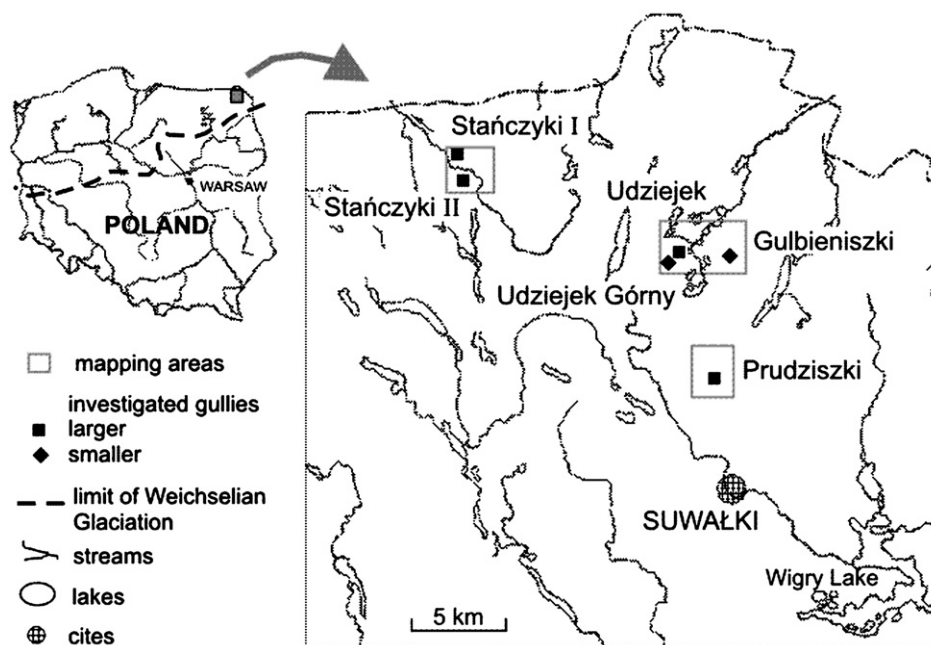


Fig. 1. Location of the study area.

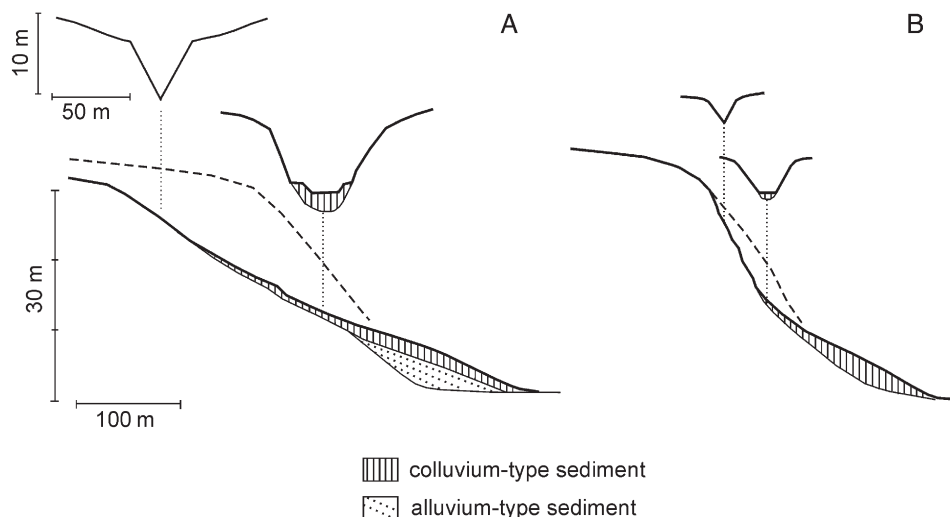


Fig. 2. Profiles through the gully thalwegs and cross-profiles larger (A) and smaller (B) gullies.

The age of the sediments was obtained by C^{14} dating of buried peat and organic mud horizons. The datings were done by the Radiocarbon Laboratories in Gliwice (*Gd-*), Łódź (*Lo-*) and Kiev (*Ki-*) using the Calib 4.4.2 calibration programme (Stuiver and Reimer, 1993).

Phases of gully erosion determined by sediments' characteristics were additionally compared with archaeological and palynological data.

4. Results

4.1. Gully morphology

The gullies in the Suwałki Lakeland are located very unevenly. In the selected areas, the drainage density is $0.2\text{--}0.5\text{ km km}^{-2}$ but locally can reach 0.8 or even 1.2 km km^{-2} (Smolska and Wasilewska, 2002). The incisions are usually located on slopes of tunnel valleys and wide depressions, particularly in the vicinity of melt-outs and lakes. These slopes have heights of over 30 m and lengths of over 100 m and are composed of sandy and gravel, sandy loams and sandy diamictons.

The gullies are mostly simple single-channel landforms and only sporadically create small dendritic systems. Considering morphology and size of the incisions, two kinds of gullies can be distinguished: the larger and the smaller ones (Fig. 2).

The larger gullies are 200–300 m long, locally over 500 m. They are cut down to 4–6 m in their upper parts and are over 10 m deep in their lower parts. The upper parts have v-shaped cross sections, while the middle and the lower parts have flat bottoms (30 to 50 m wide) and gully sides sloping from 15° to over 24° . Inclination of thalwegs is $1\text{--}2^\circ$ and the longitudinal profiles are concave (Fig. 2A). Many gullies have a 1 m high terrace in the middle of their longitudinal profiles. Fans developed at mouths of the gullies are up to

50 m long, only locally up to 80 m. The surface of the gullies and the fans are forested or have a permanent turf cover and are used as pastures.

The smaller gullies are up to 150 m long, have irregular long profiles of high inclination, average $4\text{--}6^\circ$. Their cross sections are v-shaped and the depths of the incisions are about 2 m in the upper parts and about 5 m in the middle and lower parts (Fig. 2B). The fans deposits reach 20 to 30 m (sporadically 50 m) away the gullies' mouths. Peat is found further, beyond fans in floors of depressions.

The volume of selected gullies (4 larger and 2 smaller) as well as their fans were calculated (Table 1). These forms, researched in detail, end in melt-out depressions (Udziejek, Udziejek Górny, Gulbieniszki) or in tunnel valleys (Stańczyki, Prudziszki) and they are not directly linked with current streams. Calculation of the volumes of the forms was approximated, but nevertheless, clear differences are shown between the volumes of the gullies and the fans. Compared with the volume of the whole landforms, the larger gullies have only small fans at their mouths. The fans deposited at the mouths of these gullies are relatively large and include above 75% of the material from the gully erosion.

Table 1
Volume of forms and area of gully catchments

Location of form	Length of gully (m)	Volume of forms			Area of catchment (m ²)	
		Gully (m ³)	Fan (m ³)	% of gully volume		
Larger gullies	Stańczyki 1	280	51 975	14 463	28	79 400
	Stańczyki 2	320	33 538	11 738	35	41 500
	Udziejek	560	72 337	16 796	23	65 600
	Prudziszki	350	36 094	11 219	31	45 850
Smaller gullies	Udziejek	160	1 741	1 447	83	26 816
	Górny Gulbieniszki	150	1 423	1 108	78	16 600

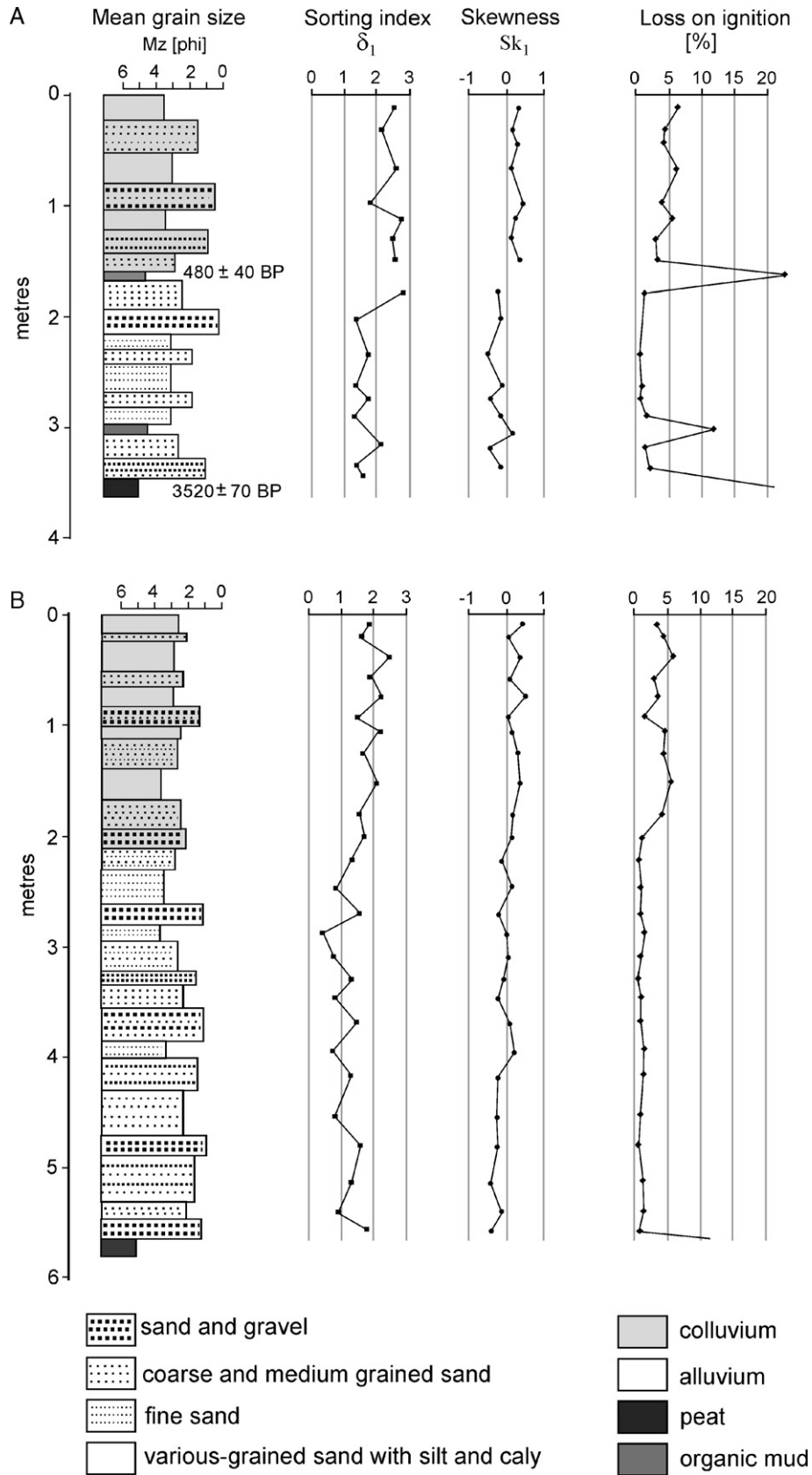


Fig. 3. Distal (A) and middle (B) part of fan deposits at mouth of larger Stańczyki I gully and sedimentological characteristics.

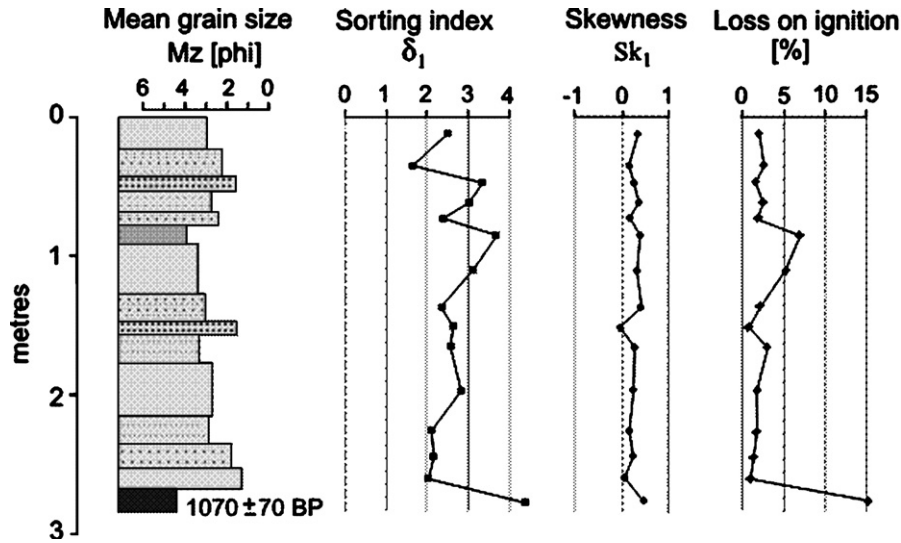


Fig. 4. Middle part of fan deposits at mouth of smaller Gulbieniszki gully and sedimentological characteristics. For legend see Fig. 3.

4.2. Sediments

The gully infillings and sediments constituting the fans were the subjects of particular interest (Smolska, 2005). Sediments deposited at mouths of the larger gullies include two characteristic units which are presented on the example of the middle and the distal parts of the fan at the Stańczyki I gully (Fig. 3). The lower unit consists of sand and sandy gravel with a mean grain diameter of $Mz=0.5-2.5$ phi (1.25–0.2 mm). The sediments are usually poorly sorted (the sorting index $\delta_1=1.2-2.2$) and coarser fractions prevail over the gains of modal size (the negative skewness Sk_1). The upper unit is composed of sand with addition of silt and clay, $Mz=2-3.5$ phi (0.25–0.18 mm) and finer fractions prevail over the grains of modal size (positive skewness Sk_1). The two units are also differentiated by organic material content (OM). The proportion of organic matter in dispersed form (humus) generally increases in the direction of the ground surface. The older, lower, yellow and beige sediment having up to 2% OM resemble alluvium. The higher proportion of organic matter in the upper and younger unit allows it to be classified as colluvium, which mainly originates from the

erosion of a humic soil horizon. The colour of the sediment unit is grey and brown.

Peat (38% OM) constitutes a substratum of the distal part of the fan (Fig. 3A). Thin layers of organic mud (11–12% OM) are found at the base of the alluvium-like older sediments (at depth of c. 3 m). Between the lower and the upper units, at a depth of 1.75–1.80 m, there is a layer of peat (25% OM). Drillings in the middle and proximal parts of the fan showed no signs of peat accumulation, nor buried soil horizons. The lower, older unit (3.5 m thick) was differentiated from the upper unit (2 m thick) based on macroscopic analysis of granulometry and colour. This differentiation was supported by granulometric indices and organic material content (Fig. 3B).

In the proximal part of the fans studied in detail in the vicinity of Udziejek, there is a third, transitional unit between the two already mentioned units that exhibits a gradual increase of colluvium (Smolska, 2005). Such a unit was also recognized in the sediments constituting a fan at a gully mouth in Prudziszki, however, the age of this units was not determined.

Older sediments are usually found in the lower strata of the fans and are 3 to 5 m thick. Younger sediments are found

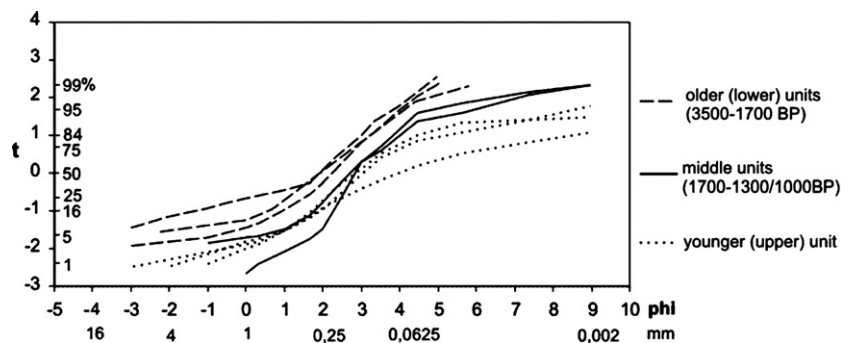


Fig. 5. Cumulative Visher curves of fan deposits, typical for particular units.

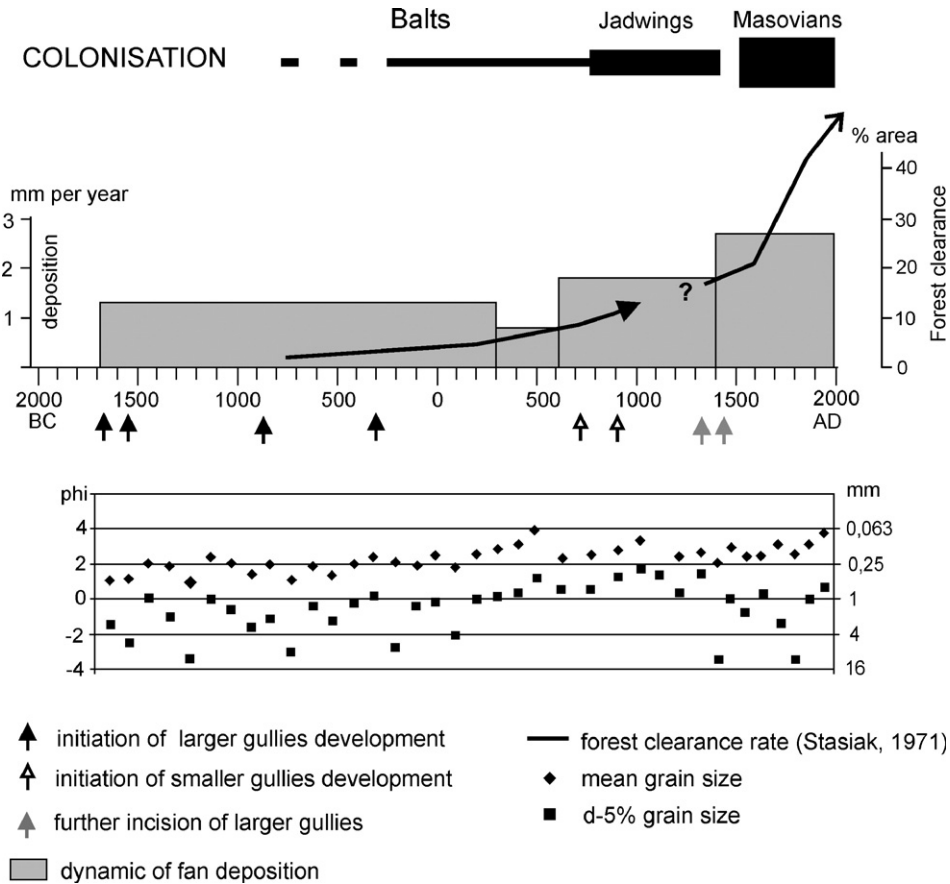


Fig. 6. Stages of gully development on the background of colonisation phases and deforestation of study area (according to Stasiak, 1971) (A) and the changes of mean grain diameter and d-5% grain size on example of fan deposits near Udziejek (B).

in the upper strata having 2–3 m of thickness, as in the case of the fan at the mouth of Stańczyki I gully or also constitute the sides of the fans, as in the case of the fan near Udziejek.

Fans deposited at the mouths of smaller gullies are maximum 3 m thick. Detailed research was performed on 2 forms near Gulbieniszki and Udziejek Górny because they are typical for the Suwałki region. Sediments building fans at the mouths of smaller gullies have a high share of fine fraction (silts and clays), poor sorting and 3–5% OM. Such characteristics liken them to sediments constituting the upper units of fan sediments at the mouths of larger gullies (Fig. 4). The fan sediments at a mouth of the smaller gully near Udziejek Górny cover a proximal part of a fan developed at a mouth of a larger gully.

The mechanisms of sediment transport are reflected in granulometric cumulative curves according to Visher (1969) (Fig. 5). The sandy gravel of the lower, older unit resembling alluvium is characterised by cumulative curves with easily defined sections indicating saltation and traction. In the same unit, sand is characterised by a small proportion of deposition from suspension (up to 10–15% of the sediment mass). These sediments originated from bottom and bank erosion of the gullies, mainly due to dissection of fluvioglacial sands and gravels, which have only a small share of silt and clay fractions. Deposition from suspension increases in the younger

sediments. In the transitional unit, the proportion of sediments deposited from suspension is 20% of the sediment mass. The proportion of material deposited from suspension in the younger sediments, constituting the upper fan units of larger gullies and all fan of smaller gullies is between 30 and 50% of the sediment mass. This reflects relatively quick and easy delivery of soil eroded from catchment areas of the studied gullies after forest clearance and introduction of agriculture.

Granulometric cumulative curves also show the proportion (%) of sediments deposited from traction (rolling and sliding) as well as the size of grains transported in traction, and therefore the energy of the depositional environment can be assessed. Granulometry of older units (alluvium type) shows that grains exceeding 1 mm in diameter were transported in traction. For younger units, the diameter of such grains slightly exceeds 0.5 mm. The middle unit is characterised by the smallest grains transported in traction.

Based on the dating of peat found under sediments of 4 different fans at the mouths of larger gullies, it is inferred that gully erosion started from 3520 ± 70 to 2240 ± 100 BP. Distinct change in the sedimentation happened between 1310 ± 60 and 1070 ± 70 BP.

Gully infillings consist mainly of younger sediments including colluvium. The sediments typical of the older unit are exposed only locally.

Table 2
Age, thickness of gully deposits at the middle part of fans and average intensity of accumulation

Location and form	Thickness of deposition (cm)	Age of colluvium		Mean annual rates of deposition (mm)
		BP	cal.	
Stańczyki 1 fan	350	3520±70 <i>Lo-964</i>	1921–1744 BC	1
	130	480±40 <i>Lo-963</i>	1411–1445 AD	2.71
Terrace	85	610±50 <i>Lo-962</i>	1340–1369 AD	1.42
		850±80 <i>Ki-10363</i>	1156–1264 AD	1.39
Stańczyki 2 fan	260	3500±130 <i>Ki-10727</i>	1980–1681 BC	1.08
Udziejek fan	450	2240±100 <i>Gd-4092</i>	321–227 BC	2.01
	250	890±90 <i>Gd-2597</i>	1039–1142 AD	2.81
	150	690±60 <i>Gd-12135</i>	1275–1320 AD	2.17
Prudziszki fan	320	2640±70 <i>Ki-10728</i>	890–880 BC	1.2
Udziejek Górny fan	40	1730±70 <i>Ki-10365</i>	240–400 AD	0.8
	210	1310±60 <i>Ki-10366</i>	661–728 AD	1.6
Gulbieniszki fan	280	1070±70 <i>Ki-10363</i>	893–1022 AD	2.6

The fans at the mouths of smaller and shorter gullies are built of younger sediments, mostly the soil colluvium. In the vicinity of Udziejek Górny and the Gulbieniszki, the age of two fans was obtained: 1310±60 and 1070±70 BP.

Characteristics of the sediments constituting the gully infillings as well as the fans show rhythmic deposition (Figs. 3 and 4). The rhythm is reflected in the older unit (alluvium) by relatively high variations in the mean grain diameter, while in the younger unit (colluvium) by variations in the proportion of dispersed organic material. The maximal grain diameter in both units is similar, which testifies to a similar intensity of extreme rainfalls. Coarse sediments underlying gully infillings – gravel and sandy gravel in Udziejek and a pavement from glacial till in Stańczyki and Prudziszki – limited further incision of the gullies.

5. Discussion

The morphology of the researched gullies clearly depends on their age. Larger, more deeply incised gullies with flat bottoms are older. Relatively small fans deposited at their mouths are probably the result of only the last Holocene development linked with gullying. This explains the major discrepancies between the volume of the gullies and the volume of the fans (Table 1). A similar situation was described by Klimek (2003) who also paid attention to discrepancies between the size of a dry valley and its fan. The larger gullies

developed along former melt-water valleys or bowl-shaped dry valleys (dellies). These old valley forms were partly modified and only some were totally reshaped by gully erosion.

Contemporary catchments of the larger, older gullies have considerably large areas (Table 1). An index often used to assess erosion intensity based on the catchment area and volume of gully does not reflect the dynamics of gully erosion in the researched region. Sediments deposited in the fans developed at the mouths of larger, older gullies as well as at the mouths of smaller and younger gullies most probably constitute a complete record of gully erosion because they were accumulated on a flat bottom of a wide depression or on wide valley floors. In the Suwałki Lakeland, the thickness of each of the fan units provides the bases for assessing gully erosion dynamics.

The dating, rate of fan deposit accumulation and lithological features of the analysed sediments allow us to determine of 4 stages of gully erosion (Fig. 6). Based on thickness of the sediments and their age, the rate of accumulation can be calculated (Table 2). This provides information about the dynamics of the processes. The older sediments of the alluvium type were accumulated at a rate of 1 mm a⁻¹ (Stańczyki I) to 2 mm a⁻¹ (Udziejek), average 1,32 mm a⁻¹. The younger sediments with colluvium were accumulated faster, particularly their upper layer, where the rate of accumulation reached 2.71–2.81 mm a⁻¹.

These stages of gully erosion were compared with archaeological and palynological data. The first farmers (the Balts) settled in this area in the second half of the first century BC (Brzozowski et al., 1993). Their arrival is reflected by the appearance of cereal pollens in peat and lacustrine deposits, although these pollen types constitute a very small proportion of total pollen (Stasiak, 1971; Kupryjanowicz, 2004). The abundance of fish and game in lakes and forests did not encourage intensive cultivation of land, therefore, forest clearance proceeded very slowly. Based on cereal pollen content and haymaking indices, Stasiak (1971) estimates that the forest was cleared on 5–7% of the area in the 2nd and 3rd century AD but it was mostly as pasture land.

The first stage (from 1500 BC to 3rd century AD) of the development of the gullies was probably determined by climatic factors, because erosion began at the bottoms of the dellies before forest clearance. Dellies, having highly inclined, long profiles, were cut and then the incisions were widened. This period produced the oldest sediments (alluvium type) deposited at mouth of the gullies. Such a process of deposition continued until about the 3rd century AD. The fan stratigraphy provided no information about possible breaks in deposition as they have no buried soil horizons. This allows us to interpret that erosion and accumulation were not very intensive and abrupt but rather proceeded with a stable limited intensity.

Such a situation is not typical for Central Europe. In Poland, the beginning of the gully erosion was triggered by forest clearance and the expansion of farmland starting with the Bronze Age, for example Sinkiewicz (1994, 1998),

Zgłobicki et al. (2003), locally with the Neolithic (Śnieszko, 1995; Klimek et al., 2003). Usually human impact on the environment is recorded in the slope deposits infilling small valleys as long as the climatic impact does not exceed the threshold for gullying (Maruszczak, 1986; Bork, 1989; Twardy, 1995; Bork et al., 1998; Dotterweich et al., 2003; Twardy, 2005) and the process is thought to be rapid (Vanwallegem et al., 2005). Studies of Belyaev et al. (2005) revealed that the development of certain gullies in the Russian Plain was not due to human activity but rather caused by natural environmental processes. They obtained dates for the correlating sediments which are similar to the dates obtained in this work for northeastern Poland (around 3.5 and 2.0 ka BP). This correlation is probably not random and suggests that the erosion was triggered by climatic factors during this more humid periods of the late Holocene (Starkel, 1995, 1998; Starkel et al., 2006).

The second stage of the gullies development (between 3rd and 7th AD) is characterised by markedly slower rate of accumulation within the fans (Fig. 6A) accompanied by slow infilling of the gullies. Sediments from this stage have gradually increasing proportion of colluvium reflecting a gradual clearing of forest and delivery of humus matter by surface wash.

Occurrence of new, smaller landforms mark the third stage of the gullies development (between 7th and 14 or 15th centuries AD). This phase was accompanied and determined by intensive development of Jadwings culture settlements. This is shown by occurrence on fans at the mouths of smaller gullies which are mainly consist of colluvium delivered from sloping cultivated land. The localisation of such gullies is totally independent of the dellies network.

The last stage (after the 14th to 15th centuries AD) is characterised by an intensive incision of infilling of the larger gullies and deposition at their mouths. The high rate of this process and delivery of large amounts of soil from deforested gully catchments can be interpreted as a result of climatic changes (Little Ice Age) and human influence. Intensified gully during the Little Ice Age was suggested by Maruszczak (1986), Bork (1989), Burczyński (1989/1990), Bork et al. (1998), Stankoviansky (2003).

Textural parameters can provide useful information about the depositional environment. The energy of water and its transporting capability is, for example, reflected by mean (M) and maximal grain diameters (Passega, 1964; Passega and Bryamjee, 1969). Because the size of maximal particles in study deposits is very similar, this study focused on the percentage by weight of the size fraction coarser than 5% of the sediment mass (d-5%). This allows us to approximate the diameters of grains which can be transported by rolling and sliding (Fig. 5). Coarse grains transported by water flow along the bottom of a gully and then are deposited on the fan point at a relatively high intensity flow, which in turn is dependant on rainfall intensity. The grain size calculated for the analysed sediments corresponds well with determined stages of the gullies' development, which is best seen in the phi-scale (Fig. 6B). Rainfalls of higher intensity during the

first and the fourth stage can be suggested by a d-5% value of grains, ranging between 0.8 to almost 16 mm. The second and the third stages are characterised by a d-5% value of grains between 0.25 and 4 mm, although the majority of samples display a d-5% value of grain close to 0.25.

Change in the type of deposition due to intensification of surface soil erosion from cleared catchments is reflected by an increasing proportion of fine grains in fans and gully infills and by the smaller values of mean grain diameters in the fan deposits. Forest clearance and the introduction of cultivation on slopes can enhance the supply of fine sediment, rich in organic matter from the soil humus horizon as during the second, and particularly the third and fourth, stages of gully erosion. Also Twardy (1995) proved that the share of organic material (%) can be successfully used to differentiate sediments derived from gully erosion and soil erosion. Material from eroded soils usually contains more organic matter (humus) and has a high share of fine fraction (silts and clays), therefore their mean grain size diameter is smaller. This is an area requiring further research.

6. Conclusions

The results of this study show that differences in the topographical situation of gullies developed in last-glacial landscape are linked to their origin and age. The larger gullies occurring along dellies are older and their incision began around 3500 and 2000 BP, long before forest clearance. The smaller gullies occur on slopes of tunnel valleys and wide depressions and their development are linked to intensive rainfalls and cultivation of slopes.

Based on the age and lithology of the sediments and the rate of the fan development, four stages of the gully erosion were determined. The analysis of the Visher's granulometric curves, and values of mean grain size and d-5%, allowed us to identify the mechanisms of sediments transport. In post-glacial areas of differential lithology these values show the sources of the delivered sediments and the intensity of rainfall, and can help to identify past settlement and agricultural activities in areas where archaeological evidence is lacking.

The first of gully erosion stage in the studied area was triggered by natural climatic changes linked to the humid periods of the late Holocene. The next stages are linked to both human and climatic influences.

Acknowledgements

This research was conducted as a part of the research projects KBN 6 PO4E 02312. I wish to thank Irene Marzolf and Allan James for providing helpful review comments.

References

- Belyaev, V.R., Wallbrink, P.J., Golosov, V.N., Murray, A.S., Sidorchuk, A.Y., 2004. Reconstructing the development of a gully in the upper Kalous Basin, Stavropol Region (Southern Russia). *Earth Surf. Processes Landf.* 29, 323–341.

- Belyaev, V.R., Eremenko, E.A., Panin, A.V., Belyaev, Y.R., 2005. Stages of late Holocene gully development in the central Russian Plain. *Int. J. Sediment Res.* 30 (3), 224–232.
- Ber, A., 2000. Plejstocen Polski północno-wschodniej w nawiązaniu do głębszego podłoża i obszarów sąsiednich. *Pr. Państw. Inst. Geol.* 170, 1–89 (in Polish, with English summary).
- Bork, H.-L., 1989. Soil erosion during the past Millennium in Central Europe and its significance within the geomorphodynamics of the Holocene. In: Ahnert, F. (Ed.), *Landforms and Landform Evolution in West Germany*. Catena, Suppl. 15, pp. 121–131.
- Bork, H.-L., Bork, H., Dalchow, C., Faust, B., Piorr, H.-P., Schatz, T., 1998. *Landschaftsentwicklung in Mitteleuropa*. Klett-Perthes, Stuttgart. 328 pp.
- Brzozowski, J., Iwanowska, G., Okulicz-Kozaryn, J., Siemaszko, J., 1993. Dzieje zasiedlenia Suwalszczyzny od epoki kamienia do wczesnego średniowiecza. *Przewodnik LXIV Zjazdu PTGeol. na Ziemi Suwalskiej 9–12 września 1993*, pp. 108–126 (in Polish).
- Burczyński, J., 1989/1990. Rozwój wąwozów na Roztoczu Gorajskim w ostatnim tysiącleciu. *Ann. Univ. Mariae Curie-Skłodowska. Ser. B* 44/45 (4), 95–104 (in Polish, with English abstract).
- Dotterweich, M., 2005. High-resolution reconstruction of a 1300 year old gully system in northern Bavaria, Germany: a basis for modeling long-term human-induced landscape evolution. *The Holocene* 15 (7), 994–1005.
- Dotterweich, M., Schmitt, A., Schmidtchen, G., Bork, H.-R., 2003. Quantifying historical gully erosion in northern Bavaria. *Catena* 50, 135–150.
- Folk, R.L., Ward, W., 1957. Brazos River bar: a study in the significance of grain size parameters. *J. Sediment. Petrol.* 27, 3–26.
- Józefaciuk, Cz., 1991. Procesy spłukiwania i erozji wąwozowej. In: Starkel, L. (Ed.), *Geografia Polski. Środowisko przyrodnicze*. PWN, Warszawa, pp. 420–425 (in Polish).
- Kalicki, T., 1996. Climatic or anthropogenic alluviation in Central European valleys during the Holocene? In: Branson, J., Brown, A.G., Gregory, K.J. (Eds.), *Global Continental Changes: the Context of Palaeohydrology*. Geological Society Spec. Public., vol. 115, pp. 205–215.
- Kalicki, T., Calderoni, G., Zernitskaya, V.P., 2004. River response to the Holocene climatic fluctuations: a case study from Zelvianka river valley (Belorussia). *Ital. J. Quat. Sci.* 17 (21), 165–180.
- Klimczak, R., 1988. Metoda obliczania objętości form wklęsłych i jej zastosowanie w geologii dynamicznej. *Czas. Geogr.* 59 (2), 201–208 (in Polish, with English summary).
- Klimek, K., 1988. An early anthropogenic alluviation in the Subcarpathian Oświęcim Basin. *Poland. Bull. Pol. Acad. Sci., Earth Sci.* 36 (2), 159–169.
- Klimek, K., 2002. Human-induced overbank sedimentation in the foreland of the Eastern Sudety Mountains. *Earth Surf. Processes Landf.* 27, 393–402.
- Klimek, K., 2003. Sediment transfer and storage linked to Neolithic and Early Medieval soil erosion in the Upper Odra Basin, southern Poland. In: Howard, A.J., Macklin, M.G., Passmore, D.G. (Eds.), *Alluvial Archaeology in Europe*. A.A. Balkema Publ., pp. 251–259.
- Klimek, K., Łanczont, M., Nogaj-Chachaj, J., 2003. Aluwiacja małych dolin w obrębie przykarpockiej wysoczyzny lessowej jako wskaźnik zmian użytkowania ziemi w ostatnim 1000-leciu. In: Waga, J.M., Kocel, K. (Eds.), *Człowiek w środowisku przyrodniczym - zapis działalności*. PTG Oddział Katowicki, Sosnowiec, pp. 84–89 (in Polish, with English abstract).
- Kupryjanowicz, M., 2004. Postglacjalny rozwój roślinności rejonu jeziora Wigry. Wstępne wyniki analizy pyłkowej osadów dennych z Zatoki Słupińskiej. *Rocznik Augustowsko-Suwalski IV, Suwałki*, pp. 37–44 (in Polish, with English abstract).
- Lang, A., 2003. Phases of soil erosion derived colluviation in the loess hills of South Germany. *Catena* 51 (3–4), 209–221.
- Lang, A., Höhnscheidt, S., 1999. Age and source of soil erosion derived colluvial sediments at Vaihingen-Enz, Germany. *Catena* 38, 89–107.
- Maruszczak, H., 1986. Tendencje sekularne i zjawiska ekstremalne w rozwoju rzeźby małopolskich wyżyn lessowych w czasach historycznych. *Czas. Geogr.* 57 (2), 271–282 (in Polish, with English abstract).
- Maruszczak, H., 1991. Wpływ rolniczego użytkowania ziemi na środowisko przyrodnicze w czasach historycznych. In: Starkel, L. (Ed.), *Geografia Polski. Środowisko przyrodnicze*. PWN, Warszawa, pp. 190–205 (in Polish).
- Passega, R., 1964. Grain size representation by CM patterns as a geological tool. *J. Sediment. Petrol.* 34, 830–847.
- Passega, R., Bryamjee, R., 1969. Grain size image of clastic deposits. *Sedimentology* 13, 830–847.
- Poesen, J., Nachtergaele, J., Verstraeten, G., Valentin, C., 2003. Gully erosion and environmental change: importance and research needs. *Catena* 50, 91–133.
- Sidorchuk, A.Y., Golosov, V.N., 2003. Erosion and sedimentation on the Russian Plain, II: the history of erosion and sedimentation during the period of intensive agriculture. *Hydrol. Process.* 17, 3347–3358.
- Sinkiewicz, M., 1994. Paleogeograficzna wymowa budowy stożków napływowych w okolicy Biskupina na Pojezierzu Gnieźnieńskim. *Acta Univ. NC, 27, Nauki Mat.-Przyr.* 92, 35–56 (in Polish, with English abstract).
- Sinkiewicz, M., 1998. In: Niewiarowski, W. (Ed.), *Rozwój denudacji antropogenicznej w środkowej części Polski północnej*. Wyd. UMK, Toruń (in Polish, with English summary).
- Smolska, E., 2005. Znaczenie spłukiwania w modelowaniu stoków młodoglacjalnych (na przykładzie Pojezierza Suwalskiego). *WGSR UW, Warszawa*.
- Smolska, E., Wasilewska, A., 2002. Cechy neoholocentrycznych osadów stokowych na przykładzie parowów na zboczach doliny Błędzianki (Pojezierze Suwalskie). In: Turkowska, K., Dzieduszyńska, D. (Eds.), *Transformacja systemów fluwialnych i stokowych w późnym wistulianie i holocenie*. UŁ, Łódź, pp. 20–21 (in Polish).
- Stankoviansky, M., 2003. Historical evolution of permanent gullies in the Myjava Hill Land, Slovakia. *Catena* 51, 223–239.
- Starkel, L., 1995. The pattern of the Holocene climatic variations in central Europe based on various geological records. *Quaest. Geogr., Spec. Issue* 4, 259–264.
- Starkel, L., 1998. Frequency of extreme hydroclimatically — induced events as a key to understanding environmental changes in the Holocene. In: Issar, A.S., Brown, N. (Eds.), *Water, Environment and Society in Times of Climatic Changes*.
- Starkel, L., 2005. Anthropogenic soil erosion since the Neolithic in Poland. *Z. Geomorphol. N.E. (Suppl. 139)*, 189–201.
- Starkel, L., Soja, R., Michczyńska, D.J., 2006. Past hydrological events reflected in Holocene history of Polish rivers. *Catena* 66, 24–33.
- Stasiak, J., 1971. *Holocen Polski północno-wschodniej*. Rozprawy UW, PWN, Warszawa.
- Stopa-Boryczka, M., Martyn, D., 1986. *Klimat. Województwo Suwalskie - studia i materiały*, vol. 1. OBN Białystok i IGI PZ PAN, Warszawa, pp. 81–118 (in Polish).
- Stuiver, M., Reimer, P.J., 1993. Extended ¹⁴C database and revised CALIB radiocarbon calibration program. *Radiocarbon* 35, 215–230.
- Śnieszko, Z., 1995. Ewolucja obszarów lessowych Wyżyn Polskich w czasie ostatnich 15 000 lat. *Wyd. UŚ, Sosnowiec*. 122 pp. (in Polish, with English summary).
- Twardy, J., 1995. Dynamika denudacji holocentrycznej w strefie krawędziowej Wyżyny Łódzkiej. *Acta Geogr. Lodz.* 69, 213 pp. (in Polish, with English summary).
- Twardy, J., 2002. Etapy neoholocentrycznej ewolucji suchych dolin denudacyjnych na Wyżynie Łódzkiej w świetle analizy osadów. *Acta Universitatis Nicolai Copernici, Geogr.* 32-Nauki Mat.-Przyr. 109, 127–137 (in Polish, with English summary).
- Twardy, J., 2005. Gully erosion in the middle Poland. In: Zgłobicki, W., Rejman, J. (Eds.), *Human Impact on Sensitive Geosystems*. Maria Curie-Skłodowska University Press, pp. 129–142.
- Vanwallegheem, T., Bork, H.R., Poesen, J., Schmidtchen, G., Dotterweich, M., Nachtergaele, J., Bork, H., Deckers, J., Brüsch, B., Bungeneers, J., De Bie, M., 2005. Rapid development and infilling of a buried gully under cropland, central Belgium. *Catena* 63, 221–243.
- Visher, G.S., 1969. Grain size distributions and depositional processes. *J. Sediment. Petrol.* 39, 1074–1106.

Zglobicki, W., Rodzik, J., Schmitt, A., Schmidtchen, G., Dotterweich, M., Zamhöfer, S., Bork, R.-H., 2003. Fazy erozji wąwozowej w okolicach Kazimierza Dolnego. In: Waga, J.M., Kocel, K. (Eds.), *Człowiek w środowisku przyrodniczym - zapis działalności*. PTG Oddział Katowicki, Sosnowiec, pp. 234–238 (in Polish, with English summary).

Zolitschka, B., Behre, K.-E., Schneider, J., 2003. Human and climatic impact on the environment as derived from colluvial, fluvial and lacustrine archives — examples from the Bronze Age to the Migration period, Germany. *Quat. Sci. Rev.* 22, 81–100.