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THE INFLUENCE OF PIPING ON MID-MOUNTAIN RELIEF: A CASE STUDY FROM THE POLISH BIESZCZADY MTS. (EASTERN CARPATHIANS)

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Abstract: The influence of piping on the mid-mountain areas mantled with Cambisols under a temperate climate is very important. The detailed geomorphological mapping was conducted in four selected catchments from the Polish Bieszczady Mts. of Eastern Carpathians. A number of 451 piping forms and 136 related features (pipe inlets and outlets) were mapped in the field. It allows coming to a modified classification of piping forms and related features together with detailed morphometric characteristics. Usually, the pipes develop up to 0.77 m depth and at the outlet their mean width is 0.30-0.40 m and height is 0.30-0.50 m. On the land surface closed depressions and sinkholes indicate piping activity. The evolution of these forms result in blind gullies formation. Moreover, piping causes the formation of depositional forms, such as piping fans. All these forms develop both on the grassland and forest on slopes with an average gradient of 12°. The role of piping as a morphogenetic process in the study area it is reflected in the formation and developing of the new and existing gullies. Pipes also occur in gullies subjected to landslides, and this is the result of adjustment to new runoff conditions. The overall results indicate that piping is included among the geomorphological processes in a mountainous region with Cambisols, not previously thought of as a piping-prone type of soils.

Key words: piping; piping forms; gully development; Cambisols; mid-mountains

1. INTRODUCTION

Piping is the process of the mechanical removal of soil particles by concentrated subsurface flows (Boucher, 1990; Jones, 2004), thereby creating underground channels (pipes). Traces of piping become visible on the surface only when a pipe roof collapses, or a pipe inlet or a pipe outlet has been located. Some researchers expand the definition of piping to include the chemical effects of groundwater, and distinguish physical and chemical piping (Maruszczak, 1986). However, according to the traditional definition piping is understood as a process of mechanical flushing of particles by underground streams (Klimaszewski, 1978; Bryan, 2000; Jones, 2004). Undoubtedly, the chemical activity of subsurface flow (e.g. solution) can facilitate piping.

There was a detailed discussion of the concept of piping in the 1990s (Dunne, 1990; Bryan & Jones, 1997). This related to the various processes which lead to subsurface erosion and to those mechanisms which influence the formation of subsurface pipes. The processes of seepage erosion and tunnel erosion were singled out. Dunne (1990) suggested that the term ”piping” should be replaced. However, as he noted himself, these processes are not mutually exclusive, although the mechanisms of their action are different. Realizing the difficulty in separating these two processes, Bryan & Jones (1997) proposed keeping the concept of piping in defining all subsurface erosion processes, that is how this concept is sometimes understood in the literature on the subject (e.g. Bryan, 2000; Jones, 2004; Desir & Marín, 2011; García-Ruiz, 2011). More often it is narrowed down to tunnel erosion (Farifteh & Soeters, 1999; Botschek et al., 2002; Romero Díaz et al., 2007; Wilson, 2009; Verachtert et al., 2010, 2011a, b; Nadal-Romero et al., 2011). Piping is also thought of as a type of soil erosion. These studies involve determining the amount of sediment concentrations in pipeflow (Bryan & Harvey, 1985;

Jones, 1987; Botschek et al., 2000; Zhu et al., 2002; Wilson, 2009), or determining erosion rates by estimating the volume of soil due to a pipe collapsing (Kerényi, 1994; Beckedahl, 1996; Botschek et al., 2000; Zhu, 2003).

Piping as a process shaping relief was neglected for many years. Studies focused mainly on the role of surface flow (Dunne, 1990; Bryan, 2000), which was significantly influenced by work of R.E. Horton (1945). It was only in the 1960s and 1970s that the impact of subsurface flow on the formation of storm hydrographs was noticed and research on subsurface erosion (piping) began to be carried out in different parts of the world (Bryan & Jones, 1997). In the 1980s and 1990s, the first comprehensive research on the impact of piping on relief development, including in particular gully development, was carried out (Jones, 1981; Bryan & Yair, 1982; Harvey, 1982; Crouch, 1983; Imeson, 1983; Baillie et al., 1986; Gerits et al., 1987; Parker et al., 1990; Bocco, 1991; Poesen et al., 1996). This work is still ongoing. It was stressed that once gullies develop, soil degradation processes, including piping, come into play (Poesen et al., 2003). The impact of pipe enlargement on gully head cut retreat (Billi & Dramis, 2003; Vandekerckhove et al., 2003) and gully wall retreat was also uncovered (Poesen et al., 2003). There was also emphasis on the fact that a pipe collapse leads to the formation of new gullies (e.g. Beckedahl, 1996; Faulkner et al., 2004; Valentin et al., 2005; Verachtert et al., 2010; Faulkner, 2013).

Current research into piping is conducted in different climate zones, and in areas with a variety of erodible and dispersive materials. Bryan & Jones (1997) distinguished three types of area in which piping is of paramount geomorphological and hydrological importance: (1) organic soils on humid uplands, (2) badlands in arid and semiarid environments, and (3) degraded semiarid rangelands, particularly in the tropics. They pointed out, however, that most research is carried out in humid regions, although the effects of piping are most visible and most easily recognizable in arid and semiarid regions. A slightly different classification was presented by Faulkner (2006), who distinguished areas with soils susceptible to piping in Europe: (1) organic, peat soils (Histosols) – upland areas in the Northern Europe, (2) soils developed on sodic and dispersive marine-sourced marl sediments (Xerosols) in the Southern Europe, and (3) loess-derived soils (Luvisols) in the Central Europe. The term Xerosols is not used in modern soil classification systems. The FAO/UNESCO included Xerosols in the legend of the Soil Map of the World in the 1970s (FAO, 1974). It seems that an author writing about Xerosols was thinking of Calcisols – soils with a marked accumulation of calcium carbonate according to the WRB (IUSS Working Group WRB, 2007).

Both classifications emphasize areas with materials connected with loess or high sodium content. Nevertheless they ignore the areas with other erodible materials, not connected with mentioned properties. This includes for instance the Carpathians, where Cambisols (in the meaning of the WRB soil classification; IUSS Working Group WRB, 2007) developed on a flysch-derived silty slope cover. In such an area piping forms also occur. Several papers which indicate the role of piping in the development of mountain relief in the Carpathians have been published in Poland (Czeppe, 1960; Starkel, 1960; Galarowski, 1976), in the Czech Republic (Buzek, 1969; Kirchner, 1981, 1987) and in Slovakia (Mazúr, 1963). However, these papers have not been disseminated in the international literature. Moreover, the associated research projects undertaken almost 40-50 years ago were not continued later.

Therefore, the aim of this paper is to present the role of piping in the shaping of mid-mountain areas mantled with Cambisols under a temperate climate. More specific objectives for the selected study areas in the Polish Bieszczady Mts. are: (1) to improve classification of piping forms and related features, (2) to present the morphometric characteristics of piping forms and piping systems, (3) to map the spatial distribution of piping forms, and (4) to link the occurrence of piping forms to other landforms.

2. STUDY AREA

The study area (Fig. 1) includes four catchments in the Polish Bieszczady Mts. (Fig. 1). Two of them are located in the Lower Bieszczady Mountains (Cisowiec – 4.0 km^2, Bereźnica Wyżna – 2.8 km^2), and the others in the High Bieszczady Mountains (Tyskowa – 5.2 km^2, Kińczyk Bukowski – 2.1 km^2). The Bieszczady Mts. are extending in SE Poland, near the border with Slovakia and Ukraine. They represent mid-mountains under a temperate climate. The mean annual temperature ranges from 4.0°C to 5.0°C, and in summit regions below 2.0°C (Michna & Paczos, 1972). The mean annual rainfall is 1000-1300 mm, and in the highest ridges exceeds 1300 mm (Nowosad, 1995).

Geologically, the Bieszczady Mts. are part of the Outer Carpathians folded in the Neogene. They consist mainly of layers of Oligocene-Lower

Miocene beds, belonging to the youngest Carpathian Flysch. These layers are composed of thick-bedded sandstones alternating with shales. The Bieszczady Mts. are characterized by structural relief (Starkel, 1969), and the grid layout of ranges corresponds to the grid arrangement of valleys (Henkiel, 1982). Parallel ridges in a NW-SE direction developed on resistant sandstones known as the Krosno and Cisna beds, and valleys were formed in less resistant shale layers (Haczewski et al., 2007). Maximum differences in elevation between the summit and the valley bottom reach 400-600 m. The height of ridges increases in a SE direction to more than 1,300 m (Tarnica 1,348 m a.s.l.).

Soils are formed on slope covers derived from the Carpathian Flysch (Kacprzak, 2003). In the Bieszczady Mts. Cambisols prevail (Skiba & Drewnik, 2003) and, in those areas where water flows under the surface, Stagnic Cambisols or Endogleyic Cambisols occur. The examples of typical Cambisols profiles are presented in the table 1. Thick slope covers with high silt content are prone to piping (Starkel, 1960). In addition, there are numerous channels made by burrowing animals, which may also function as pipes (Czeppe, 1960).

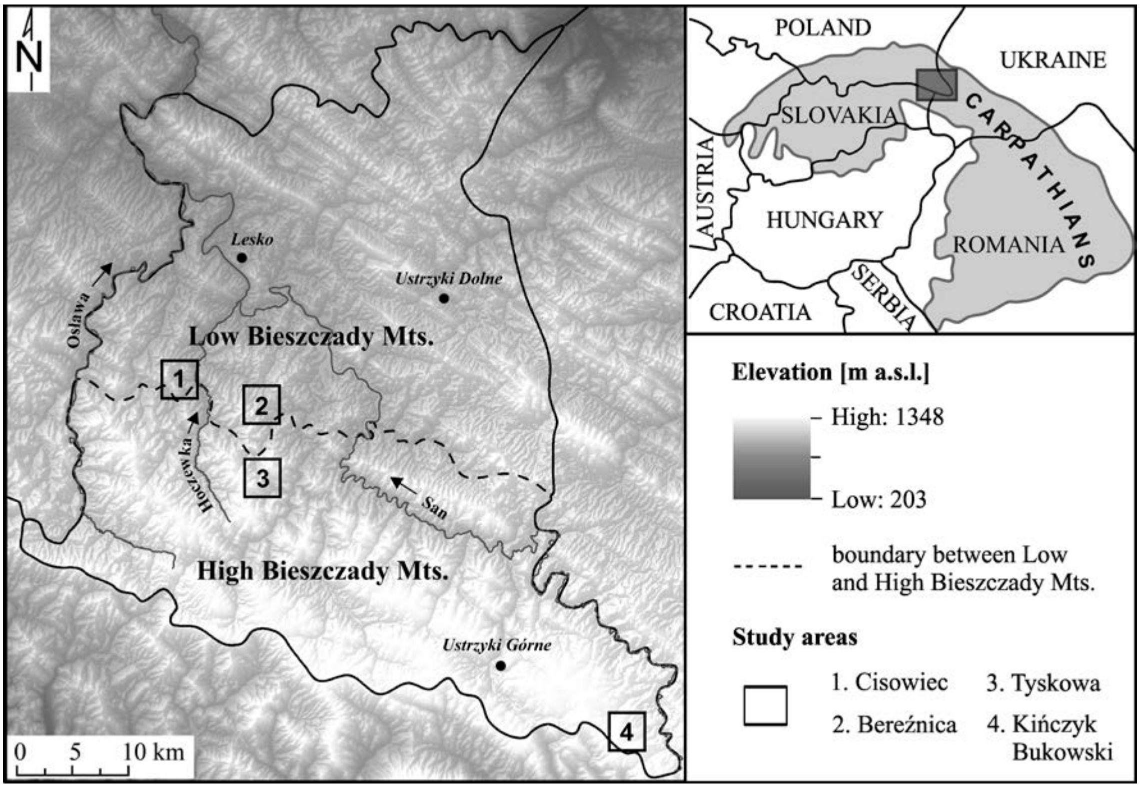

Figure 1. Location of the study area in the Polish Bieszczady Mts. of Eastern Carpathians (based on 90×90 m DEM).

Table 1. Basic physical and chemical properties of Cambisols from the Bieszczady Mts. (Kacprzak, 2003, modified).

Depth [cm]	Horizon	Fraction >2 mm [%]	Particle size distribution (φ < 2 mm)			pH		Corg [%]
			2.0-0.05	0.05-0.002	<0.002	H_2O	KCl	
Profile 1. The upper part of the SW slope of Połonina Caryńska (The High Bieszczady Mts.)								
0-5	Of	moderately decomposed organic matter				3.8	3.2	
5-15	Ah	10	41	53	6	4.2	3.6	4.68
15-50	ABbr	15	37	56	7	4.4	3.9	1.85
50-80	Bbr/C	75	33	55	12	4.5	4.1	-
80-95	C	85	47	40	13	4.5	4.1	-
Profile 2. The low part of the NE slope of Mała Rawka (The High Bieszczady Mts.)								
0-3	Of	moderately decomposed organic matter				4.1	3.4	
3-20	Ap	10	41	52	7	4.4	3.7	2.90
20-45	ABbr	25	14	64	22	5.2	4.0	0.86
45-75	Bbr/Cgg	60	22	56	22	5.7	4.4	-
75-105	Cgg	95	42	37	21	5.9	4.7	-
105-125	R							

Forest covers nearly 70% of the Bieszczady Mts., most of it in the south, especially in the Bieszczady National Park. Since the World War II, due to the displacement of the local population, there was a significant change in land use. Grasslands and pastures decreased, currently accounting for 2.5% and 9% of the area respectively, while arable land dropped to almost 18%. The farmland extends mainly in the northern, lower part of the Bieszczady Mts. (the analysis based on the Corine Land Cover 2006 project, coordinated by European Environment Agency, EEA, 2010).

3. MATERIAL AND METHODS

Prior to fieldwork, a research review was conducted. Studies into piping were carried out in the Bieszczady Mts. in the 1960s and 1970s (Czeppe, 1960; Starkel, 1960; Galarowski, 1976) in several catchments of the Upper San River. Recently, a geomorphological-geological monograph on the Bieszczady National Park was published, where several sites with collapsed pipes were indicated (Haczewski et al., 2007). In addition, interviews with the local community were undertaken. Based on this information, four catchments, which were studied 40-50 years ago (Tyskowa, Cisowiec – Czeppe, 1960; Bereźnica – Galarowski, 1976) and mentioned in later literature, have been selected for detailed fieldwork (Kińczyk Bukowski – Haczewski et al., 2007).

Pipes are located mostly through mapping collapsed pipes and their outlets or inlets (Czeppe, 1960; Jones, 1981; Verachtert et al., 2010). Detailed geomorphological mapping of collapsed pipes by using a GPS receiver (Garmin GPSMap 62s, accuracy <3 m), was carried out in 2012 and 2013. The base map was prepared at scale 1:500. The dimensions of piping forms (length, width, depth) were determined with a measuring tape.

The digital maps of catchments are based on numerical elevation data in the ESRI TIN format from 2009. There were constructed using routines available in ArcGIS 10.2 software. This data was converted into the raster format with a 10×10 m resolution. The hillslope gradient was determined. A land use map was made based on data from the Corine Land Cover 2006 project (resolution 100x100 m), and supplemented with field data collected.

4. RESULTS

4.1. The development of piping forms and related piping features on the surface

On the basis of collapsed pipes mapped in the field, and the Verachtert et al. (2010) classification, a modified version of classification of the piping forms was developed (Fig. 2). Blind gullies and piping fans are identified as forms initiated by piping and they are added to the classification. Piping forms are classified as follows:

1) **Closed depressions** which developed as result of lowering of the soil surface above a pipe, but where no break in the vegetation cover has occurred. They can evolve into sinkholes;
2) **Sinkholes** appear as vertical or nearly vertical walls that have emerged as result of pipe collapse. The bottom of these forms is also the bottom of the pipe, and the material which has collapsed sometimes is still on the bottom of the sinkholes;
3) **Blind gullies** which appear when within the same pipe several sinkholes develop and there are successive collapses of the land between sinkholes or when one sinkhole is enlarged by the collapse of a roof pipe;
4) **Piping fans** are built of material carried out of the pipe and reflect the depositional aspect of piping.

As mentioned above, the piping forms are transformed because of the pipe collapse. The evolution of piping forms leads to the gully development (Fig. 3).

Piping activity can also be detected by finding pipe inlets and outlets (Fig. 2). So that, the following features related to piping can be identified:

5) **Pipe inlet** as the place where water, flowing (permanently or temporarily) on the surface, has drilled macropores in the soil;
6) **Pipe outlet** as the place where water and the carried material emerge from pipe onto the surface and a piping fan is sometimes formed.

In selected catchments in the Bieszczady Mts., 451 piping forms and 136 pipe inlets and outlets were mapped. A detailed description of piping forms is shown in Table 2. It is worth noting that the mean depth of sinkholes in the area is 0.77 m, which is also the mean depth at which pipes developed, since the bottom of a sinkhole is the bottom of a pipe. The deepest sinkholes reach 1.60 m, and those above 1.00 m constitute 15% of all those mapped. Closed depressions are on average shallower than sinkholes, which follows from the definition of these forms and, reaching the depth of 0.46 m, they usually have a depth of 0.40 m. Blind gullies are characterized by a mean depth of 0.91 m, a value greater than the depth of the bottom of pipes (0.77 m). This is because, after the formation of a gully (from a pipe collapse), a channel develops, so the primary bottom of a pipe is deepened. A blind gully is treated as a piping form, because it arises from piping. Moreover, a three parameter analysis of variance shows that these forms differ significantly (α=0.05) from sinkholes, as presented in the figure 4.

In the selected catchments 9 piping fans were identified. Their mean thickness (freshly deposited material) is approximately 0.10 m, and their length is nearly 1.70 m and the width at the base is 1.00 m (Table 2). These forms develop at pipe outlets, but they have developed in only 7.5% of them. The small number of these forms indicates the balance between the amount of material carried out of pipes onto the surface and its discharge rate after escaping onto the surface. As to the size of a pipe, which is determined based on the parameters of pipe inlets and outlets, it should be noted that pipes are characterized at inlets by a mean width and height greater than those at outlets, with a mean width of 0.30-0.40 m and height of 0.30-0.50 m. Interestingly, the shape of pipes is rather circular, but some flattening at the bottom part of a pipe is noticeable. This proves that the water flowing in a pipe does not always fill the entire pipe. Sometimes water flows only in the lower part of a pipe and does not have enough power to transport sediments, so it is left at the bottom of a pipe.

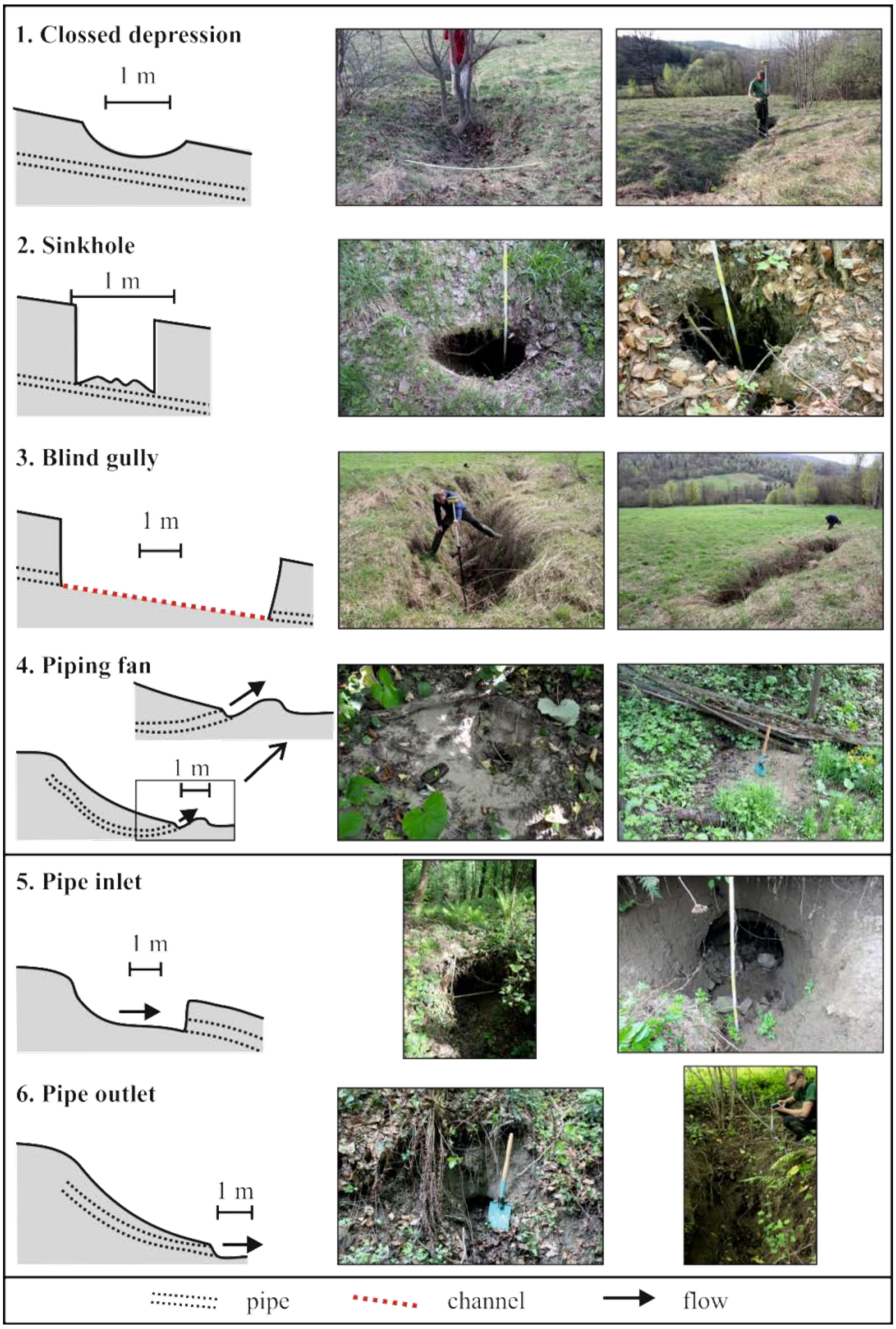

Figure 2. Classification of piping forms and related piping features (based on Verachtert et al., 2010, modified, described in the text).

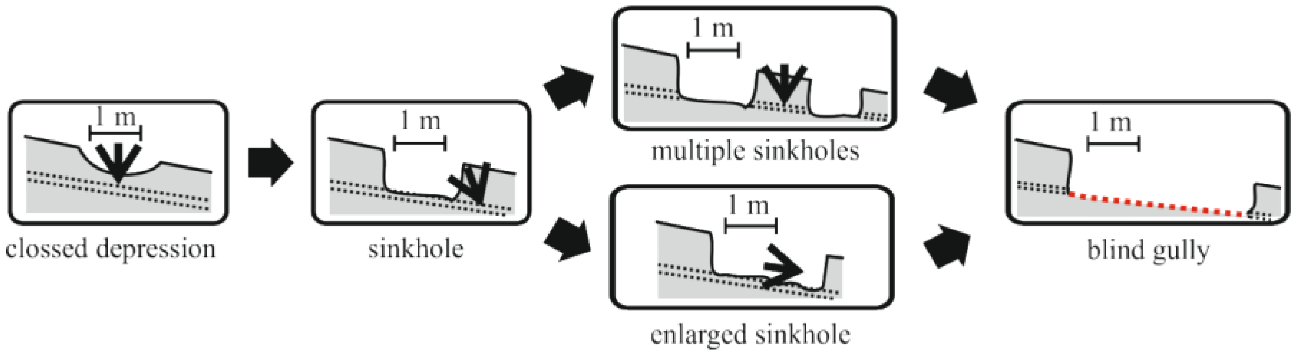

Figure 3. Evolution of piping forms.

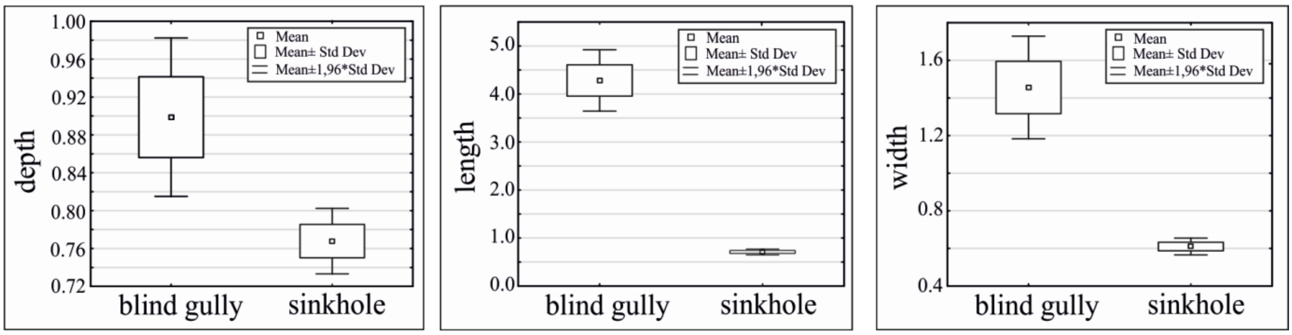

Figure 4. Box plots showing variations in the morphometric parameters (depth, length, width) between blind gullies and sinkholes.

Table 2. Morphometric characteristics of piping forms and related piping features in the selected areas in the Bieszczady Mts. (according to the classification in the Figure 2).

	Closed depressions			**Sinkholes**			**Blind gullies**			**Piping fans**			**Pipe inlets**		**Pipe outlets**		**Sum**
	d	**l**	**w**	**d**	**l**	**w**	**d**	**l**	**w**	**d**	**l**	**w**	**h**	**w**	**h**	**w**	
Mean	**0.46**	**2.71**	**1.29**	**0.77**	**0.71**	**0.61**	**0.91**	**8.60**	**1.49**	**0.13**	**1.69**	**0.99**	**0.45**	**0.52**	**0.33**	**0.38**	
Median	0.40	1.80	1.20	0.70	0.60	0.50	0.85	3.30	1.30	0.10	0.80	0.65	0.40	0.45	0.25	0.30	
Moda	0.30	1.00	1.20	0.70	0.30	0.40	1.20	1.90	1.20	0.10	0.80	0.45	0.30	0.20	0.20	0.20	
Min[1]	0.10	0.30	0.30	0.20	0.10	0.10	0.30	1.00	0.40	0.05	0.20	0.30	0.20	0.20	0.08	0.10	
Max[1]	1.50	13.50	3.50	1.60	2.60	1.90	2.50	345.00	11.00	0.25	8.00	2.50	1.20	1.20	1.20	1.40	
Std Dev	0.25	2.49	0.58	0.28	0.49	0.36	0.38	38.20	1.25	0.07	2.30	0.74	0.24	0.29	0.22	0.27	
n	116			247			79			9			16		120		587

d – depth from ground level, l – length, w – width, h – height of pipe, Std Dev – standard deviation; [m]
[1] – minimum and maximum: parameters are not from the same piping forms and features, not even from the same catchment

Table 3. Characteristics of piping systems in terms of piping forms and features number in the selected areas in the Bieszczady Mts.

Catchment	**Number of systems**	**Number of piping forms**				**Number of piping features**		**Sum**
		clossed depressions	**sinkholes**	**blind gullies**	**piping fans**	**inlets**	**outlets**	
Cisowiec	34	19	51	16	3	3	31	123
Bereźnica	37	44	90	24	3	2	29	192
Tyskowa	37	53	106	38	3	10	58	268
Kińczyk Bukowski	1	0	0	1	0	1	2	4
Sum	109	116	247	79	9	16	120	587

4.2. Characteristics of piping systems

Surface piping forms are created because pipes have developed under the surface, so that these forms are secondary to the primary ones (pipes). However, we are only aware of the existence of underground pipes when a surface form develops (derived from pipe subsidence or collapse), or when we locate a pipe inlet or outlet. Most frequently, the existence of a pipe can be inferred on the basis of several surface forms and a located pipe inlet or outlet. Such a complex of piping forms, which are associated with one or more combined pipes, constitutes a piping system. In total, 109 piping systems were located in the test areas (Table 3), and in almost every catchment the number of piping systems ranges from 34 to 37. Only in a catchment much higher above sea level, and partially above a timberline (Kińczyk Bukowski), was only one piping system mapped. Most evidence for the existence of pipes is provided by sinkholes. The lower number of closed depressions than sinkholes may be due to their low stability in the relief. The pipe roof collapses rapidly and closed depressions turn into sinkholes (Table 3). Moreover, it was not possible in every piping system to find a pipe outlet. This may be due to the diversion of underground flowing water into a number of smaller pipes, the non-concentrated subsurface flow or the inability to find an outlet because of the dense vegetation cover. The mean length of piping systems (the distance from the first, through the next, to the last located piping form or pipe outlet, calculated in a longitudinal profile) is 52.6 m, which also indicates the minimum length of pipes. The longest piping system reaches a length of 252.8 m, and in the case of Kińczyk Bukowski – 357.8 m. On average, piping systems reach a length from 20.3 to 57.6 m (Table 4). The exception is Kińczyk Bukowski, where only one system was located and in which the length of one blind gully is 345 m (Table 2). However, the length of this gully cannot be linked only to piping, but also to superficial gully erosion. After a pipe collapse superficial processes start to function.

Table 4. Length [m] of piping systems in the selected areas in the Bieszczady Mts.

Study area	Mean	Median	Max	Std Dev
Bereźnica	44.7	33.9	142.7	39.9
Cisowiec	28.1	20.3	146.6	29.5
Tyskowa	74.7	57.6	252.8	67.4
Kińczyk Bukowski	357.8	357.8	357.8	-
General	52.6	30.6	357.8	59.9

Table 5. The presence of piping forms and features (per type) on slope gradient classes.

Slope class	Closed depressions		Sinkholes		Blind gullies		Piping fans		Pipe inlets		Pipe outlets		General	
[°]	%	n	%	n	%	n	%	n	%	n	%	n	%	n
0-5	0.9	(1)	0.0	(0)	0.0	(0)	0.0	(0)	6.3	(1)	0.0	(0)	0.3	(2)
5-8	5.2	(6)	12.1	(30)	10.1	(8)	22.2	(2)	0.0	(0)	8.3	(10)	9.5	(56)
8-15	81.0	(94)	73.7	(182)	77.2	(61)	66.7	(6)	62.5	(10)	70.0	(84)	74.4	(437)
15-25	12.9	(15)	13.4	(33)	12.7	(10)	11.1	(1)	31.3	(5)	21.7	(26)	15.3	(90)
25-30	0.0	(0)	0.8	(2)	0.0	(0)	0.0	(0)	0.0	(0)	0.0	(0)	0.3	(2)
Sum	100	(116)	100	(247)	100	(79)	100	(9)	100	(16)	100	(120)	100	(587)
Mean	**12**		**12**		**12**		**12**		**12**		**13**		**12**	

Table 6. The presence of piping forms and features (per type) on land cover classes.

Land cover class	Closed depressions		Sinkholes		Blind gullies		Piping fans		Pipe inlets		Pipe outlets		General	
	%	n	%	n	%	n	%	n	%	n	%	n	%	n
Grassland and pastures	56.9	(66)	54.7	(135)	64.6	(51)	33.3	(3)	12.5	(2)	20.8	(25)	48.0	(282)
Forests	37.9	(44)	31.6	(78)	12.7	(10)	44.4	(4)	50.0	(8)	53.3	(64)	35.4	(208)
Buffer strips	5.2	(6)	13.8	(34)	22.8	(18)	22.2	(2)	37.5	(6)	25.8	(31)	16.5	(97)
Sum	100	(116)	54.7	(247)	100	(79)	100	(9)	100	(16)	100	(120)	100.0	(587)

4.3. The spatial distribution of piping forms

The spatial distribution of piping forms in the Bieszczady Mts. was analyzed at catchment scale, varying in size from 2.1 to 5.2 km^2. The mean gradient of slopes in the catchments ranges from 10° to 15°, and on average piping forms developed on slopes with a gradient of 12°. These forms can develop on practically flat surfaces; the minimum gradient of slope on which piping forms were found was 4°, but they can also be on relatively steep slopes – up to 30°. However, almost 75% of piping forms occur on slope with a gradient of between 8° and 15°.Looking separately on the different types of piping forms and features the general trend is confirmed – every type of forms mostly develop on slope 8°-15°. Only closed depressions and piping inlets occur on almost flat surface (>5°), whereas only sinkholes were found on steep slope (25°-30°) (Table 5). So although these forms do usually develop on slopes with an average gradient for whole catchment.

The distribution of piping forms in relation to land use was analyzed in the light of two types of land use – grasslands and pastures as well as forests, with the addition of a third type, namely buffer strips, which are understood as linear clusters of trees that do not form a dense forest complex, and occur mainly along gullies. Most sinkholes and closed depressions (respectively 54.7% and 56.9%) develop on grasslands and pastures. A consequence of this is the fact that most blind gullies (64.6%) also develop in grasslands and pastures. Piping outlets and inlets generally occur (more than 50.0%) in forest (Table 6).

In contrast, when it comes to whole piping systems, these mostly develop in the upper part in grasslands and in the lower part in forests (40 mapped systems, representing almost 40% of the whole). This means that the land use does not stop the development of pipes. There are 31 systems which are only in forests (29% of all systems), 26 (24%) – only in grasslands, and 12 (11%) – only in buffer strips.

4.4. The location of piping forms in relation to other landforms

The distribution of piping forms can be considered in relation to other landforms. Piping forms can develop independently of existing gullies.

They can also occur in relation to already existing gullies. On the one hand, these forms occur above existing gullies, where the pipe outlet of a given system is located in the headwaters of a gully (Fig. 5, 6). On the other, these forms, and consequently pipes, may develop in the bottom of existing valleys, leading to their deepening (Fig. 6). In addition, places where there are indications of piping forms can be regarded as places for the potential development of new gullies. All the piping forms and related piping features mapped are presented on maps (Fig. 7).

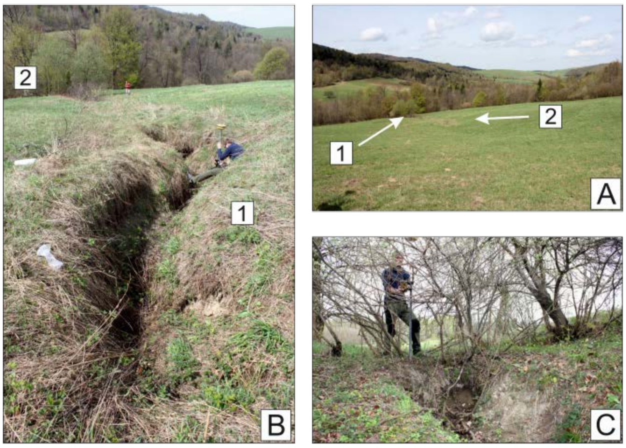

Figure 5. Piping system developed above the existitng gully: A – an overview of the gully (in forest – 1) and piping system (in grassland – 2); B – piping system above the gully; C – pipe outlet in the channel head.

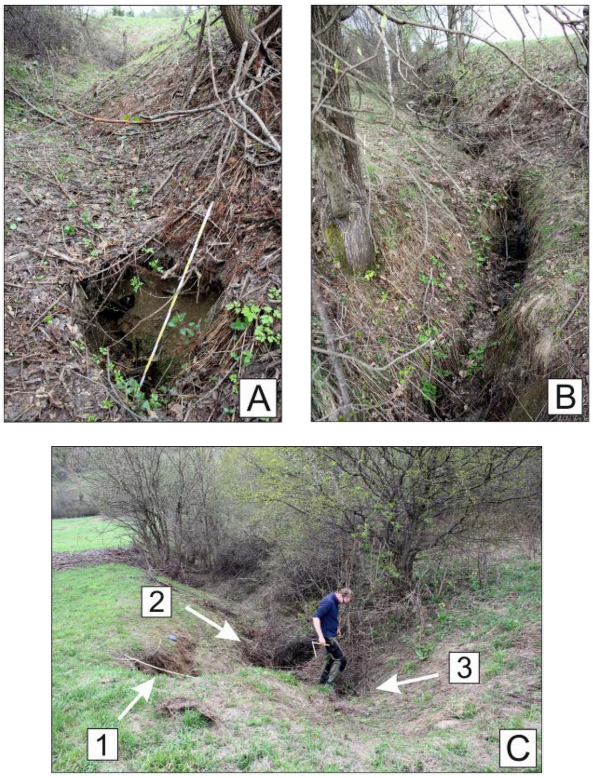

Figure 6. Piping system developed in the existing gully: A – sinkhole in the bottom of a gully; B – blind gully in the bottom of an existing gully; C – an overview of the headwater area (1 – pipe outlet, 2, 3 – sinkholes).

There was only a relationship between mass movements and piping in one system (i.e. in the Tyskowa catchment). The piping system developed within a gully transformed by landslide processes. The appearance of colluvial materials in the gully caused the obstruction of the surface water flow, resulting in infiltration and the development of a pipe.

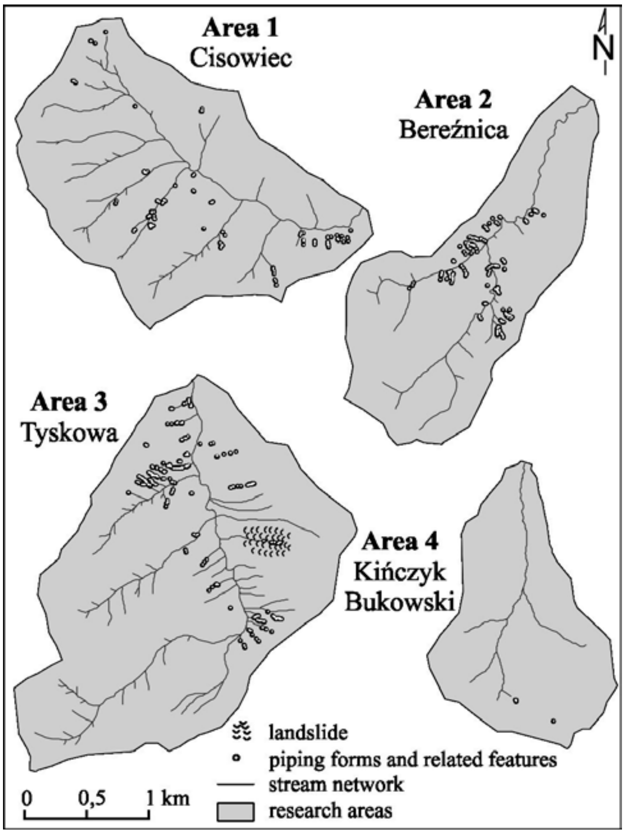

Figure 7. Spatial distribution of collapsed pipes and their relationships with a drainage network.

5. DISCUSSIONS

5.1. Piping as a morphogenetic process

Piping is treated as a type of subsurface erosion (Bryan & Jones, 1997). Moreover, this concept is more and more frequently referred to as soil piping erosion (Poesen et al., 2003; Zhu, 2003; Faulkner, 2006; Wilson, 2009; Verachtert et al., 2010, 2011a, b). It is noteworthy that although piping is primarily involved in developing erosional forms such as pipes, sinkholes, closed depressions or blind gullies, depositional forms, such as fans (piping fans) created by material carried out of a pipe, also develop. These depositional forms were not mentioned by Verachtert et al., (2010) in a loess area in central Belgium in presenting the classification of collapsed pipes and related piping features. However, the formation of such forms during the late winter thawing was noted in the Lublin Upland of the southern Poland, and they were referred to as a "deposition fan from piping processes" (Rodzik et al., 2009). These forms occur also in the Bieszczady Mts. Their occurrence was noted by Starkel (1960), who described them as "a fan". The present study found only 9 (out of 587 of all piping forms and features mapped). However, their existence proves the depositional nature of piping.

A blind gully also creates an independent piping form. It owes its origin to piping and the morphometry is different from other piping forms. It can be treated either as a further stage in the development of multiple sinkholes (Verachtert et al., 2010), or resulting from the enlargement of a single sinkhole. These forms were mentioned among other piping forms by Czeppe (1960) and Starkel (1960) and referred to as "a blind piping gully" or just "a piping gully".

5.2. The morphometry and morphology of piping forms

The mean depth of pipe in the research areas in the Bieszczady Mts. (Eastern Carpathians) is 0.77 m, and ranges from 0.20 to 1.60 m. In the Western Carpathians, in the north-eastern Czech Republic, this depth ranges from 0.47 to 2.25 m (Demek et al., 2012). In the loess area of central Belgium, the mean depth of sinkholes, and thus of the bottom of pipes is 0.60 m (Verachtert et al., 2010), and in Germany it ranges from 1.50 to 2.00 m (Botschek et al., 2002). However, in the badlands of southern Spain, pipes develop at a depth of 3.00-4.00 m in the vicinity of Almería (Faulkner et al., 2000), and on average from 1.00 to 2.50 m, with a maximum of 8.00 m near Murcia (Romero Díaz et al., 2007). Thus, the depth of a pipe depends on the type and thickness of the material in which the piping process occurs. In areas with Cambisols, the mean depth of pipes does not exceed 0.60-0.70 m, whereas in thick loess-derived soils (Luvisols), they can achieve a depth of between 0.60 m and 2.00 m, and in badlands in marl lithologies (Calcisols) pipes can develop at depths ranging from 1.00 to 3.00-4.00m, with a maximum of up to 8.00 m.

Mean pipe sizes can be determined based on the width and height of pipe inlets and outlets. In the Bieszczady Mts. they are around 0.30-0.50 m. These values are slightly higher than those described and listed in the early 1990s for temperate climate zones (Jones, 1994), when the average diameter of pipes was approximately 0.30 m (Jones, 1994). It should be emphasized that pipe diameters should be measured in two dimensions (width and height), because these forms are not always circular in cross-section, but also oval. These two values are only given in a few papers (Botschek et al., 2002), in most cases only the diameter being provided (Jones, 1994; Verachtert et al., 2010; Zhu, 2012). Giving only the value of the diameter of pipes can be insufficient in certain areas and leads to ignoring their shape. The shape of a pipe is important because it can indicate the power of a stream and the amount of water flowing in it. An oval shape means that water sometimes flows only at the bottom of a pipe, which causes greater erosion of the pipe walls at the bottom. The water in a pipe then behaves like a river which erodes laterally, first to the right then to the left, making the channel wider. An oval shape may also be a result of the deposition of transported material in a pipe, and the consequent flattening of its bottom part.

5.3. The distribution of piping forms

In the literature the discussion on which slope gradient is favored in pipes development is still ongoing. Some researchers indicate that pipes are more common on steeper slopes (Jones, 1981; Gutiérrez et al., 1997). Steeper hydraulic gradients are more likely to result in pipe formation, because there is greater shear stress on macropores and pipe walls. Nevertheless, there is a threshold of slope gradient where water infiltration decreases and surface runoff increases (Jones, 1981), which may lead to the development of landslides rather than pipes. In contrast to these results, in blanket peats in UK more pipes develop on gentler slopes along valley floors and hilltops (Holden, 2005), where the peat structure plays greater role than the hydraulic gradient. In the Bieszczady Mts. pipes occur in Cambisols on slopes with a gradient of 8°-15°, up to a maximum of 30°, what is slightly similar to loess-derived areas (with Luvisols), where these values range from 4°-11° (Belgium, Verachtert et al., 2010) to 14°-24° (New Zealand, Gibbs, 1945). It seems that in these areas there is no preference for slope gradient, which supports earlier scientific reports presented by Starkel (1960) in the Carpathians. The pipes do usually develop on slopes with an average gradient for whole catchment. Therefore, it seems that those physical, soil or hydraulic conditions emphasized by other authors (Jones, 1981; Verachtert et al., 2010), will be of greater importance in the development of these forms. This requires further research.

In the Bieszczady Mts., pipes were found in areas of different types of land use (Tab. 6). More collapsed pipes (surface piping forms) occur in grasslands and pastures, which confirms earlier results. For example, in Belgium (Verachtert et al., 2010) and in Germany (Botschek et al., 2002) piping activity is observed mainly in grasslands. The dense vegetation cover, such as grassland, provides good soil erosion control , but may promote infiltration, so consequently also piping (Stocking, 1988). However, piping systems in the Bieszczady Mts. frequently develop both in grassland and in forest. Their upper part is usually located in grassland, while pipe outlets are located in forest. This layout is connected to the gully network, which extends mostly under forest in the mid-mountains of SE Poland.

5.4. The impact of piping on relief

The impact of piping on the development of gullies has long been described in the literature (Jones, 1981; Bryan & Yair, 1982; Harvey, 1982; Geritis et al., 1987; Calvo Cases & Harvey, 1996; Gutiérrez et al., 1997; Farifteh & Soeters, 1999; Faulkner et al., 2004; Valentin et al., 2005; Frankl et al., 2012; Faulkner, 2013). In Poland, the impact of piping on the development of gullies has been highlighted in the loess area of the Lublin Upland (Rodzik et al., 2009). By comparing the gully network to collapsed pipes it can be stated that also piping plays a role in the development of gullies in the Bieszczady Mts. Pipes developing independently of the existing gully network will form a new gully after a complete pipe roof collapse. This process takes place gradually, as evidenced by the initial formation of closed depressions and sinkholes, and the subsequent development of blind gullies. Moreover, pipes which are above existing gullies guide their development, and also confirm the impact of piping on their origin and evolution (Fig. 5, 7). These conform to cases already described in the literature (Billi & Dramis, 2003; Poesen et al., 2003). In addition, pipes which develop in existing gullies cause them to deepen (Fig. 6).

In the catchments studied in the Bieszczady Mts. only one example of the coexistence of piping and mass movements was found. In Tyskowa, a landslide transformed the gully and the colluvial material blocked the surface runoff. Pipes arose, because the water had to adjust to the new flow conditions. Other relationships between piping and mass movements are known in the literature. On the one hand, mass movements may be a secondary consequence of enlarging pipes (Temple & Rapp, 1972; Bruthans et al., 2012; Faulkner, 2013). On the other hand, fractures formed as a result of landslides can develop into pipes (Jones et al., 1997). In addition, mass movements can destroy existing pipes (Farifteh & Soeteres, 1999).

6. CONCLUSIONS

This study shows that piping is among the geomorphological processes in the Bieszczady Mts., which represents mid-mountains with Cambisols under a temperate climate. Complex surface forms that have developed within one or several combined pipes, known in this paper as piping systems (as in Czeppe, 1960; Galarowski, 1976; Beckedahl, 1996), are evidence of piping and the existence of underground pipes. The piping forms can be seen as:

a) primary, underground forms (pipes) and secondary, surface forms (sinkholes, closed depressions, blind gullies and piping fans),
b) erosional forms (pipes, sinkholes, closed depressions, blind gullies) and depositional forms (piping fans).

According to the morphometric parameters the pipes in the Bieszczady Mts., which develop in Cambisols on silty slope covers are slightly smaller than the forms that are in loess areas in Luvisols. Their mean depth is similar, but maximum depths are greater in loess-derived areas, where covers are thicker than in Cambisols in the Carpathians. Also, pipes in semiarid regions with Calcisols (with high exchangeable sodium content) like the badlands in Spain have a different morphometry. However, these results from the Bieszczady Mts. draw attention that piping should be taken into account in areas with Cambisols, not previously thought of as a piping-prone type of soils.

Moreover, the morphometric analysis and spatial distribution of piping forms allows us to recognize the role of piping in the shaping of mountain relief. Piping, therefore, should be studied in the mountainous areas, alongside other geomorphological processes. In the Bieszczady Mts., piping primarily affects the development of gullies. Areas where there are piping systems are with a potential for the formation of new gullies, and also where piping can exert an influence on the future development of existing ones.

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