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IMPACT OF LAND USE CHANGES ON COLLAPSED PIPES DEVELOPMENT IN THE LOESS GULLY (LUBLIN UPLAND, EAST POLAND)

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Abstract: Subsurface erosion is a poorly recognized but important process for modelling and predicting gully erosion rates in loess areas. It is crucial to recognize the factors and mechanisms of soil piping and pipe collapse development. Our research is the first detailed description of the complex evolution of large collapsed pipes on the banks of a loess gully over 25 years (west part of Nałęczów Plateau, Lublin Upland). The objective of this study was to reconstruct the development of piping forms as a result of land use change. Detailed field observations and measurements after snowmelt and rainfall-runoff events formed the basis of the research. Sedimentary structures observed in the walls of recently collapsed pipes, filling up older piping forms, were studied. The human impact on the development of collapsed pipes has been significant. We found a multi-stage development of these forms with several cut and fill phases. An important factor influencing the formation and development of these forms was the change in land use (crop type and tillage direction). Farmers tried to reclaim collapsed pipes by filling them in with soil and incorporating them into the cropland. The resulting depressions had high infiltration rates resulting in a reactivation of soil piping processes. Increase of precipitation and the intensity of runoff caused the secondary stage of collapsed pipes development (with a volume ranging between 240 and 912 m^3 per collapsed pipe). Changing runoff patterns as a result of human interventions decreased their activity, but caused the development of new (secondary) collapsed pipes.

Keywords: piping, land reclamation, agrarian pattern changes, gully erosion, loess

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Introduction

Soil piping is subsurface erosion caused by concentrated runoff. It is an important and widespread land degradation process leading to significant soil losses and morphological changes in almost all climatic zones and under various land use conditions (Bernatek-Jakiel, Poesen 2018, Poesen 2018). The network of subsurface pipes may collapse, and thus generating collapsed pipes with varying size: sinkholes (single and multiple), closed depressions, blind gullies (Verachtert et al. 2010, Bernatek 2015). Although the process may occur in various sediments, silty deposits especially loess sediments are very susceptible to piping (Faulkner 2006, Rodzik et al. 2009, Verachtert et al. 2010, Bernatek-Jakiel et al.

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2016, 2017, Poesen 2018). Avalaible studies, suggest that piping is affected by numerous natural factors including topography, local hydraulic gradient, lithology, physical and chemical properties of the soils, vegetation as well as climate (Verachtert et al. 2013, Bernatek-Jakiel, Poesen 2018, Rafaeli et al. 2023). Additionally, factors that allow infiltration of runoff, e.g. presence of cracks in the soil (Pengchong et al. 2024) and a water-restrictive layers which induces a lateral subsurface flow may initiate piping (Faulkner 2006, Verachtert et al. 2013, Bernatek-Jakiel, Poesen 2018). Land use and management are highlighted as important factors controlling piping development. Several studies report that piping may occur in pastures due to intense biological activity (Verachtert et al. 2013, Bernatek 2015, Wilson et al. 2015, Poesen 2018) as well as in croplands that may turn into abandoned fields (Llena et al. 2024). In temperate zones piping forms have also been reported in forests (Rodzik et al. 2009, Bernatek-Jakiel, Wrońska-Wałach 2018). The impact of land management on collapsed pipe development, especially the role of parcel borders is rarely reported (Gardziel, Rodzik 2005, Kołodyńska-Gawrysiak et al. 2024).

Loess is a specific sedimentary rock, plastic and prone to washout in the wet state, while relatively resistant in the dry state (Frankowski, Grabowski 2006). This allows loess to maintain steep slopes and even vertical walls. In many parts of the Lublin Upland loess covers are dissected by gullies (Gawrysiak, Harasimiuk 2010). The edges of permanent gullies are particularly threatened by erosion including piping. The gully edge determines steep local hydraulic gradients. If concentrated surface runoff from agricultural fields reaches the edge of a forested gully, rill and headcut erosion as well as piping start to develop (Rodzik et al. 2021, Kołodyńska-Gawrysiak et al. 2024). Thus piping contributes to the spatial development of gullies. The role of piping in initiating, transforming and enlargement of gully systems both in loess cover and other substratum is underlined by many authors (Poesen et al. 1996, 2003, Faulkner et al. 2004, Gardziel, Rodzik 2005, Rodzik 2010, Rodzik, Zgłobicki 2010, Dotterweich et al. 2012, Desir, Marín 2013, Faulkner 2013, Superson et al. 2014, Vanmaercke et al. 2016, Bernatek-Jakiel, Poesen 2018, Zgłobicki et al. 2020, Rafaeli et al. 2023). Moreover soil piping represents a hazard for land management resulting in loss of agricultural areas (Verachtert et al. 2011, Zhu 2012, Bernatek-Jakiel et al. 2017).

Our research falls within the scope of the studies on gully development (among others: Poesen 1989, 2018, Poesen et al. 1996, 2003, Malik 2008, Rodzik 2010, Zhu 2012, Castillo, Gómez 2016, Vanmaercke et al. 2016, Pengchong et al. 2024).

The main objective of the study was to recognize indirect and direct human effects on pipe collapse development. Our study fills a research gap regarding the impact of land cover changes on the initiation of piping and the subsequent development of sinkholes and collapsed pipes. Research conducted to date on the effects of land cover and land cover change on piping has focused on areas of pasture and woodland (Verachtert et al. 2010, Bernatek-Jakiel, Kondracka 2019). Most of the collapsed pipes were found on pastures. Our study is the first attempt to describe the development of pipe collapses in banks of loess gullies. The novelty of the research lies in the detailed study of the development of piping forms located on the forest edge below agriculturally used slopes. To date, in the loess areas of eastern Poland, research has been conducted primarily on historical gully erosion, gullies as records of human activity, the conditions and dynamics of the development of such forms (e.g. Schmitt et al. 2006, Rodzik et al. 2009, Zgłobicki, Baran-Zgłobicka 2011, Dotterweich et al. 2012, Superson et al. 2014, Rodzik et al. 2024). The study area is characterised by the presence of a specific land use, creating a mosaic of crops that influences the conditions for the development of gullies, including piping (Zgłobicki, Baran-Zgłobicka 2012).

Study area

Kolonia Celejów catchment is located in the western part of the Nałęczów Plateau, Lublin Upland. Almost the entire catchment area is occupied by a loess cover, deposited mainly in the last pleniglacial (Fig. 1). It contains thicker deposits and a lot of calcium carbonate (>10%). This makes it extremely unstable in structure and sensitive to water erosion (Malinowski 1959).

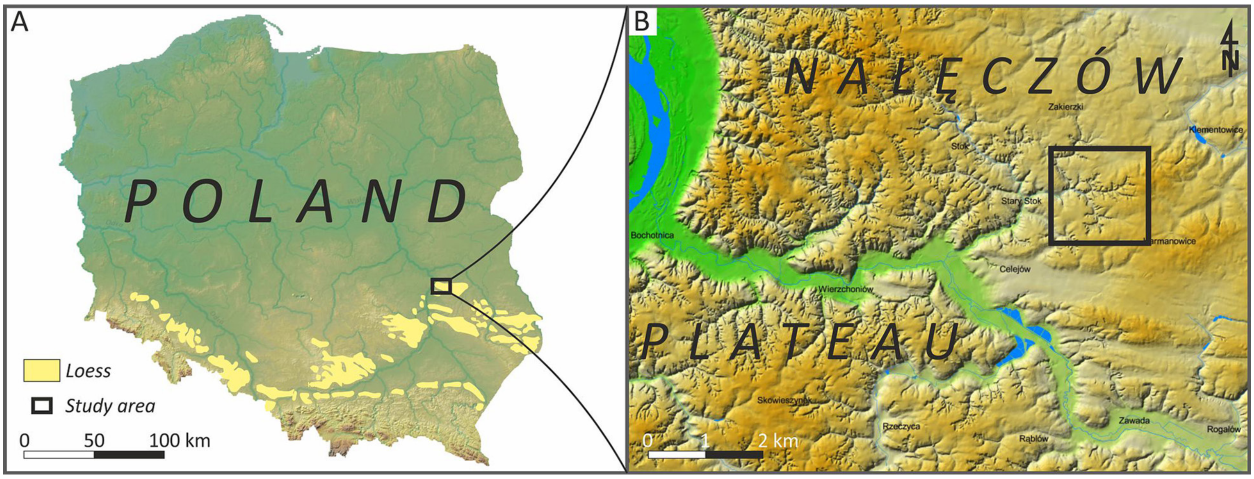

Fig. 1. Location of the Kolonia Celejów gully catchment, A) against the Polish loess belt (Główny Urząd Geodezji i Kartografii. 2024. LiDAR. Access November 2024. https://www.geoportal.gov.pl/; loess cover after Maruszczak 1991), B) in the western part of the Nałęczów Plateau.

Therefore, in the bottoms of dry valleys in the study catchment, the thin (3–10 m) loess cover was easily cut by gully erosion. The eroded material in part was replaced by colluvial silty, silty-sandy or silty-clay sediments, 1–3 m thick, originating from modern erosion of the upper sections of the gully. Nowadays the dry valleys are dissected in many places, while the remnants build a regressive terrace (Zgłobicki, Rodzik 2007).

The main element of the catchment's relief is the undulating plateau, located at an altitude of 190–210 m a.s.l., shaped synchronously with the accumulation of loess (Fig. 2). It is diversified by shallow closed depressions, partially under conditions of agricultural use filled with products of soil erosion (Kołodyńska-Gawrysiak et al. 2018). Three shallow, side valleys and shallow slope valleys drain into the valley (Fig. 2). This system of valleys has a well-functioning surface runoff system, with a longitudinal gradient of 4–7% in the side valleys and 2–3% in the main dry valley.

The system of valleys, formed under the changing climatic conditions of the Late Glacial, was consolidated in the Holocene by the

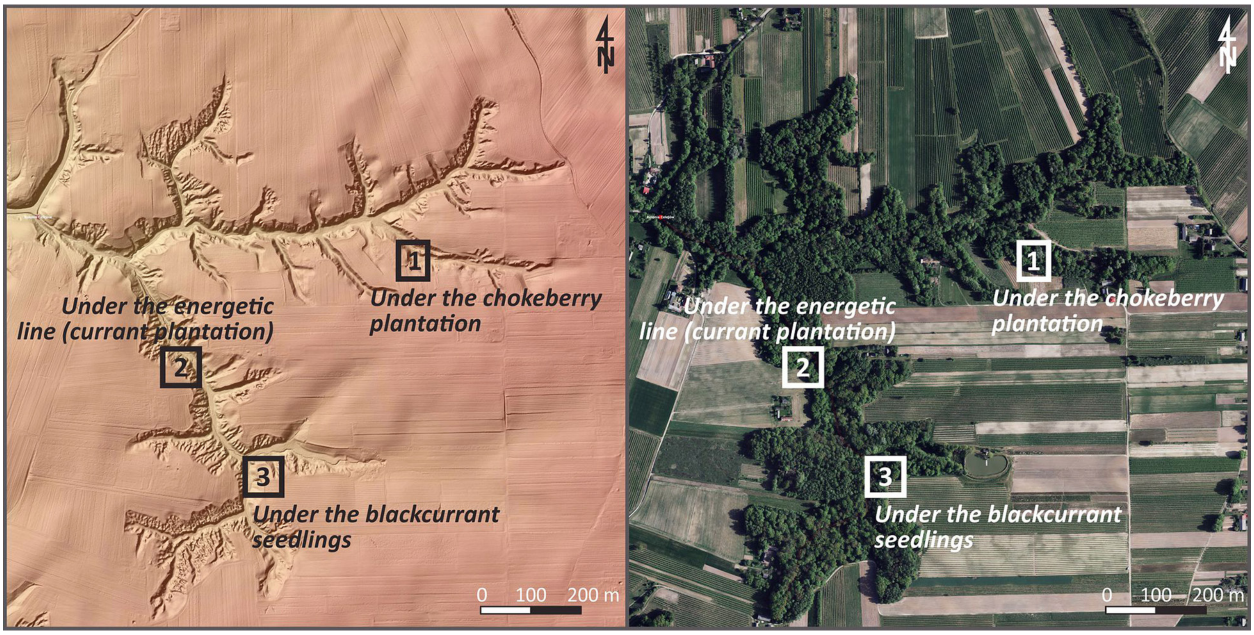

Fig. 2. Relief of gully catchment in Kolonia Celejów – DEM from 2022 (Główny Urząd Geodezji i Kartografii. 2024. LiDAR. Access November 2024. https://www.geoportal.gov.pl/) (left), and land use – Orthophotomap 2024 (right). The location of studied collapsed pipes. 1 – Site 1, 2 – Site 2, 3 – Site 3.

Tilio-carpinetum oak-hornbeam forest. Beneath it, loess soils about 1.5 meters deep with an extensive profile were formed from loess: A-Et-B1t-B2t-BC-C1-Ck. Forest clearing and soil tillage initiated erosive processes with opposing effects: sheet and tillage erosion, resulting in the smoothing of plateau and slope surfaces, and gully erosion, causing their fragmentation (Rodzik 2010, Rodzik et al. 2014). Erosion, especially gully erosion, is favored by relatively high precipitation events. The average annual total in the area is about 600 mm, the average annual number of days with high daily precipitation ≥10 mm is high – 15 (Kaszewski 2008).

The monitored sites are located within a branching, forested gully system with a total length of 7.5 km and a catchment area of 1.24 km^2. Local relief in the catchment area reaches up to 50 m (213–165 m a.s.l.), while the density of the gully network exceeds 6 km · km^{-2}. It includes: two main branches of about 1 km each, connecting into a 200-meter outlet section, and about 10 tributary gullies of 200–300 m in length. One of the main gullies is south-north (south branch) and the other east-west (north branch). The network of gullies is supplemented by blind valleys and bank gullies usually formed and modelled by piping. Sometimes bank gullies may create a set of badlands (Fig. 2).

All gullies developed in the loess cover. The larger ones additionally cut into the glaciogenic formations lying beneath the loess: fluvioglacial sands and residuals of glacial till. In places, loess directly overlies the weathered Paleocene gaizes with lenses of limestone (Harasimiuk, Henkiel 1976). Local aquifers persist on the clays and weathering, trapping water in the overlying loess cover, increasing its susceptibility to gravitational processes. After wet periods, it can result in exfiltration for a long period, feeding periodic watercourses.

Materials and methods

The field data related to the development of reactivated piping forms, was collected in the period 1997–2024. The study was undertaken in connection with the effects of snowmelt and high precipitation events that occurred in the region in 1995–2001. The first, partial inventory was made after a downpour in September 1997, another 2 years later. Since 2003, as part of a program involving comprehensive monitoring of the gully catchment (Rodzik et al. 2009), all forms of erosion and sediment accumulation in the catchment were recorded, including the volume of some piping forms. The usually limited access to piping sites precluded the use of specialized apparatus, and after erosion episodes or series of them (clustering), hand-drawn sketches, measurements with a tape, clysimeter and rangefinder were made, and photographic documentation was collected.

In 2005, a basic set of field measurements was made, the results of which became the basis for later inventories, serving as comparative material. On the basis of 52 measured points, a tachymetric photograph of the collapsed pipe located under the chokeberry was taken (Site 1). The data was used to reconstruct the phases of its development with secondary forms against the background of changes in adjacent fields and the slope of the gully. The extent of the original piping form and the process of its reclamation were reconstructed on the basis of the analysis of 31 sediment-soil profiles, exposed in the walls of the collapsed pipe or excavated with a handheld Eijkelkamp probe with a sampler, taking a core of undisturbed soil for textural analysis (Site 1). Simultaneously, simplified hand-drawn sketches and measurements of the other two sites were made (Site 2 and 3). The last measurements, sketches and photographic documentation were made in the spring of 2024. A DEM was used for visualization and measurements needed to calculate the volume of the cuts.

Environmental changes were traced on archival aerial photographs, issued every decade since the mid-20th century, provided by GUGiK (Central Office of Geodesy and Cartography in Warsaw). Several interviews were also conducted with local residents, dating back to their own memory of the first half of the 20th century, while the knowledge of the previous generation dates back as far as the late 19th century. The interviews were a valuable source of information about socio-economic changes, details of settlement history and agrarian structure, land use and forms of anthropogenic pressure, such as cattle grazing in gullies. This information was confronted with our own field observations. The analysis of the transformation of the studied forms was carried out "from the end", interpreting the learned facts and by deduction reconstructing the events of the past.

Results

Site 1: "Under the Chokeberry" collapsed pipe

The collapsed drainage channel of this catchment, with several pot holes in the bottom, cuts the edge, the waterlogged arm of the northern gully. The local relief between the bottom of the gully and the top is less than 20 m. Gully is about 10 m deep. The upper part of the gully has been transformed by a terrace at forest edge. The youngest border, located at the highest point, directs runoff along the edge of the gully (Fig. 3).

The western wall exposed a soil profile of a typical Luvisol (Fig. 3A), cut by plowing (Fig. 3B) at the low position of the forest edge, so possibly at a time not too far from the formation of the gully. The dissection of the edge forced it to move up the slope. In the resulting sinkhole, there was a sediment accumulation, originating from the outcrop – packets of different soil horizons. The vertical contact between the loess wall of the sinkhole and the infilling sediments, whose consolidation indicates an advanced age, is evident (Fig. 3C). This took place with infiltrating water, as evidenced by the laminated filling of a small channel (Fig. 3D). Reactivation of the modern sinkhole began along the western wall of its predecessor on contact with fill deposits, which were gradually removed (Fig. 4A). However, erosion did not reach the eastern wall, leaving much of the infilling sediments (Fig. 4B, C, D).

These sediments, exposed in two profiles, document the reclamation process of this sinkhole. In the profile on the line of the forest edge, three types of colluvial sediments were distinguished (Fig. 4C, D). Above the lower one-meter-long inaccessible section, located in the sinkhole,

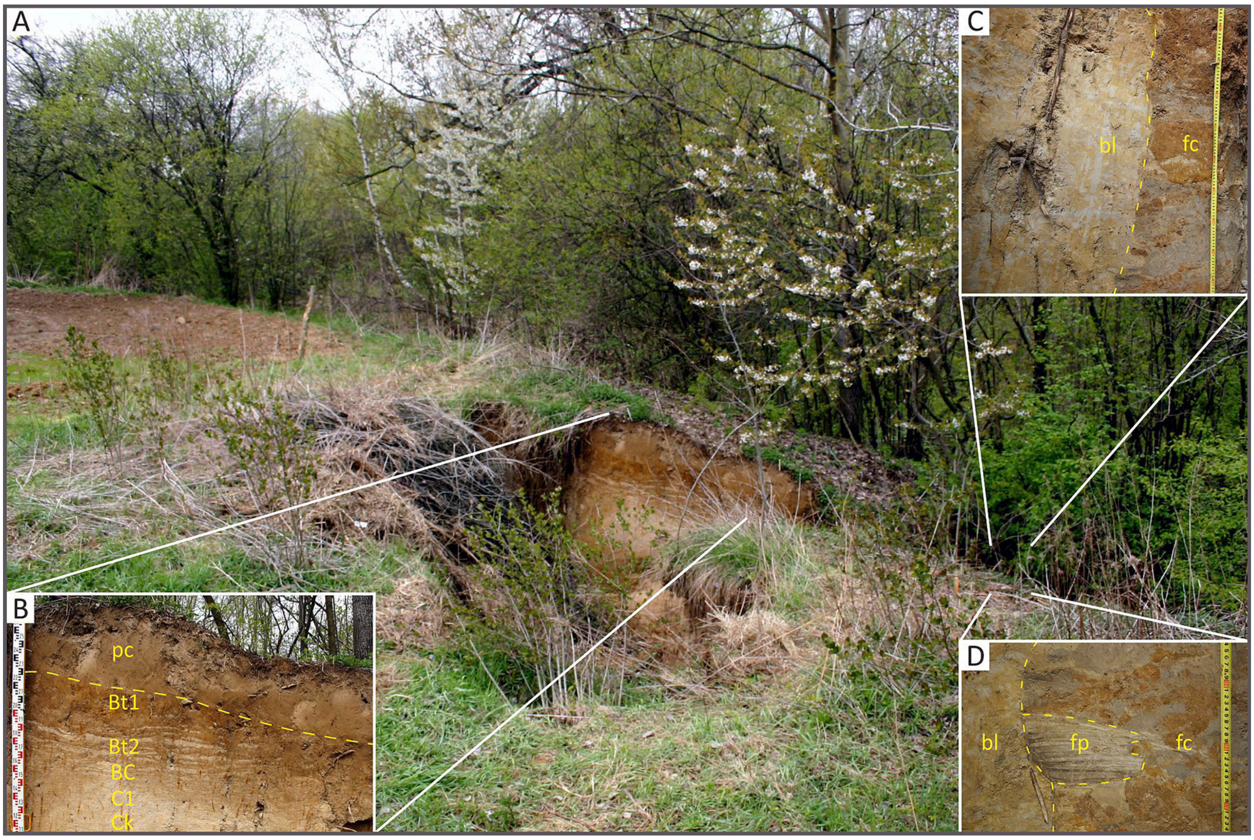

Fig. 3. Cross-section of modern forest edge (A), with truncated and overlying Luvisol profile (B): and contact of loess sinkhole wall with fill deposits (C) and silted channel (D). pc – ploughing colluvia, bl – basal loess, fc – falling colluvia, fp – fossil pipe.

Fig. 4. Dissection of the forest edge under the chokeberry plantation (A) and exposures of sediments infilling the old sinkhole (B, C, D): ac – water colluvia, fc – falling colluvia, pc – ploughing colluvia.

there are horizontally layered water-deposited sediments from the dilution of various soil horizons with a total thickness of 1.25 meters. They document the silting up of the sinkhole after closure of the channel outflow. On top of the layered sediments lies a half-meter series of deformed packets and lumps of various soil horizons. The textural features of the sediment, especially its partial mixing, may be traces of shrub clearance, overgrowing the edges of the sinkhole. Subsequently, tillage erosion caused deposition of soil into the centre of the pit, gradually made it shallower. Vegetables, especially cabbage, were grown in the reclaimed depressions due to the

Fig. 5. Development of the secondary collapsed pipe at Site 1: A – view of the collapsed pipe catchment. B – recent edge of the collapsed pipe on the agricultural terrace (white dotted line).

greater soil moisture content (Rogoza 2005 – oral information). Based on the interviews, it was assumed that agricultural use of the collapsed pipe, equivalent to its reclamation, took place between 1940 and 1995, so the rate of deposition of agricultural colluvium at the forest edge was about 4 cm per year. This is several times higher than the amount of annual deposition in the closed depressions (Rejman et al. 2014, Rodzik et al. 2014, Kołodyńska-Gawrysiak et al. 2018). In contrast, agricultural terraces, which similarly function as denudation bases on slopes, are growing at a similar rate (Ziemnicki 1968).

This sinkhole is the main part of the complex system with several secondary forms, active even during the stabilization phase (Fig. 5A). In the exceptionally quiet year of 2007, in terms of erosional processes, only one channel, draining the new western sinkhole in the complex, was reported to be discharging sediments throughout the catchment. The Site 1 complex continues to develop, especially in wet years with abundant rainfall runoff. The western collapsed pipes, in particular, is active, taking in runoff from two longitudinal fields. The change in the direction of cultivation to perpendicular to slope, which was made after the removal of the chokeberry and currant plantations, should limit its development.

Site 2: "Under the Line" collapsed pipe

The collapsed pipe, in terms of its location, size, time and conditions of development, is similar to the one discussed above. A collapsed drainage channel cuts the edge of the southern gully, overlain by colluvial sediments accumulated in a zone of two different ages of field-forest boundaries (Fig. 6). The collapsed pipe itself was cut into an agricultural terrace. located in the shallow depression and formed by the deposition of colluvial sediments (0.80–1.45 m thick).

Beneath these sediments, the walls of the collapsed pipe have preserved a Luvisol, generally with a complete profile, with the upper levels somewhat transformed by cultivation (Fig. 7A). The collapsed pipe is active and drains sediments through a drainage channel with pipes. At its outlet, a classic depositional cone has developed in the bottom of the gully (Fig. 7B). The remains of a possible older collapsed pipe were not found, despite the fact that two forest edges were found older and younger. Instead, they were found on

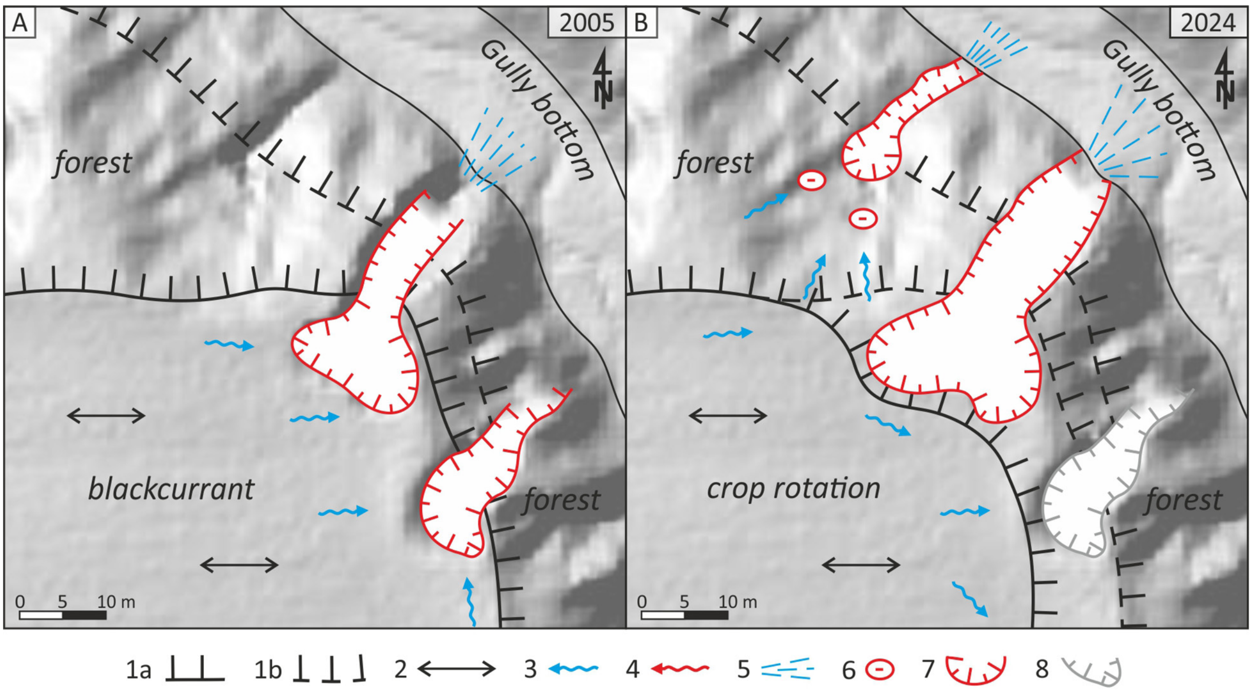

Fig. 6. Development of the collapsed pipe at Site 2, A – in 2004. B – in 2024. red arrow – erosion furrow. 1 – forest edge, 1a – contemporary, 1b – former, 2 – direction of tillage, 3 – direction of surface runoff, 4 – ploughed erosion rills; 5 – colluvial fan, 6 – sinkhole, 7 – collapsed pipe, 8 – reclaimed pipe. DEM from 2022 (Główny Urząd Geodezji i Kartografii. 2024. LiDAR. Access November 2024. https://www.geoportal.gov.pl/).

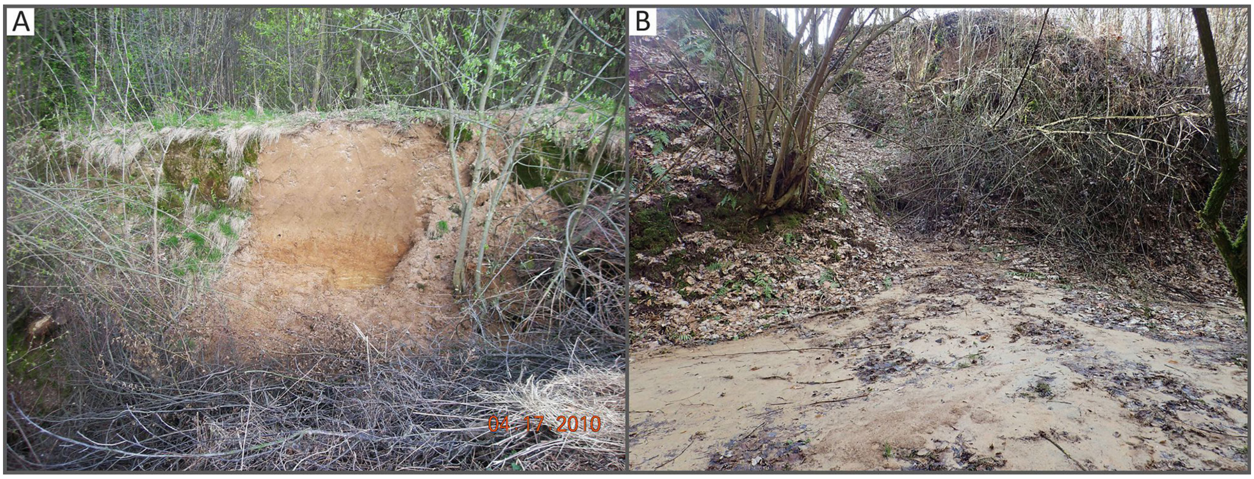

Fig. 7. The collapsed pipe at site 1: A – Luvisol and agricultural colluvia on the collapsed pipe wall. B – drainage channel with pipes and depositional cone at the outlet.

Fig. 8. The secondary collapsed pipe at Site 2: A – front loess wall with pipe, B – side wall with colluvial fill, C – drainage channel.

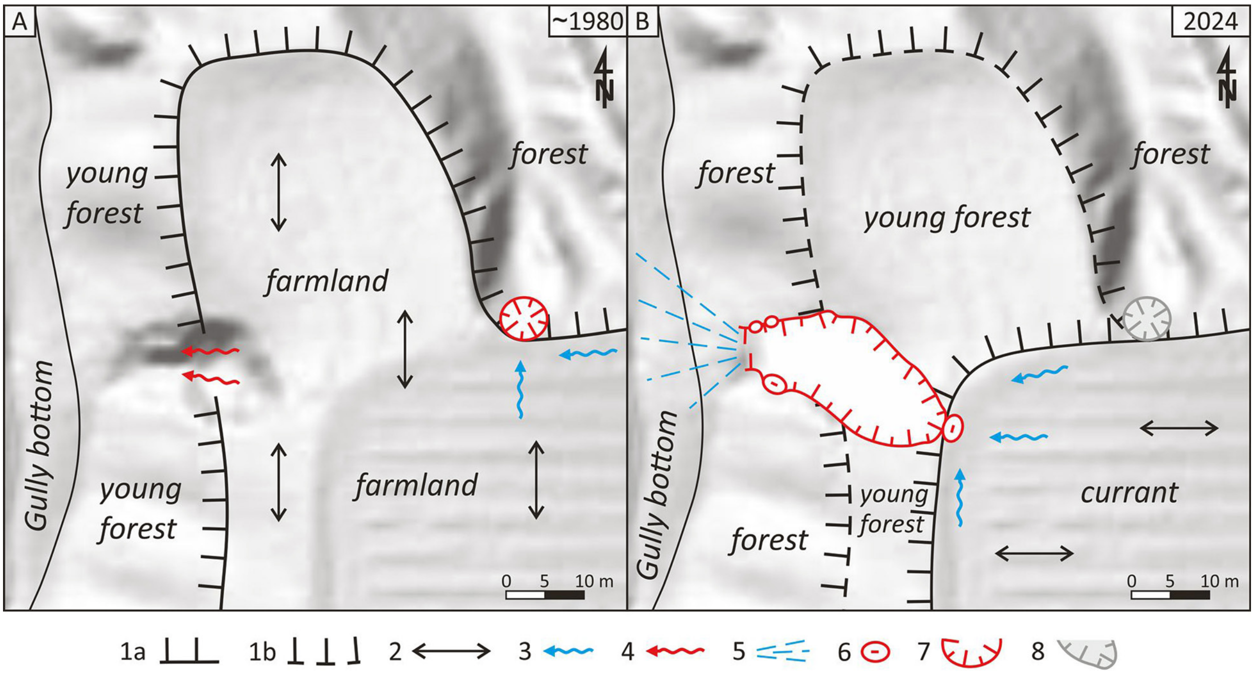

Fig. 9. Changes in the development conditions of the Site 3: A – state before 1980. B – present state. 1 – forest edge, 1a – contemporary, 1b – former, 2 – direction of tillage, 3 – direction of surface runoff, 4 – ploughed erosion rills; 5 – colluvial fan, 6 – sinkhole, 7 – collapsed pipe, 8 – reclaimed pipe. DEM from 2022 (Główny Urząd Geodezji i Kartografii. 2024. LiDAR. Access November 2024. https://www.geoportal.gov.pl/)

the walls of a secondary form that develop on a path on the slope of the gully. This path intentionally collected runoff, directly into the gully, to limit the development of the upper collapsed pipe. At the former forest edge, a new collapsed pipe was quickly formed, with characteristic rills cut into the vertical walls built in part from in situ loess and in part from colluvial packets, mostly without soil material (Fig. 9).

Site 3: "Under the Blackcurrant "collapsed pipe

The third studied collapsed pipe, the largest in the entire gully system, is located on the slope of the southern gully (Fig. 2). It is the result of dissection of the slope of gully, predisposed by agricultural use. Initially, it was a linear dissection, and over time other processes shaped it: headcut erosion in the head section and piping, mainly shaping the drainage zone. Although it originated and developed at the same time as the previous two, favourable conditions for its development occurred much earlier, when, around 1980, the cultivation of the extensive field from which runoff flows into the collapsed pipe was diverted (Fig. 9).

The shifting of the forest edge also took place in the case of this collapsed pipe. As late as the mid-1960s, the entire slope and bottom of the gully was used for agriculture at the cross-stream. The gully was abandoned around 1970, marking the forest edge on its natural edge, obliterated somewhat by agricultural cultivation. However, after the cultivation direction was changed to longitudinal, it became susceptible to piping (Fig. 10). Consequently, the boundary was moved to the slope of the plateau, which reduced the threat for a while.

At the same time, the method and type of cultivation that promotes piping and approximates this hazard was practiced. Growing currant in longitudinal rows generates and concentrates lots of surface runoff (Fig. 11A). Once a plantation begins to bear fruit, it can be kept in turf, which largely prevents flushing (sheet and rill erosion). However, in this case, currant seedlings were grown for several years in a row. Such cultivation leaves the soil in herbicide fallow, thus generating runoff in every season, concentrated in the corner of the field. This resulted in the rapid development of a single collapsed pipe (Figs 11B, 12), whose volume approaches 1000 m^3.

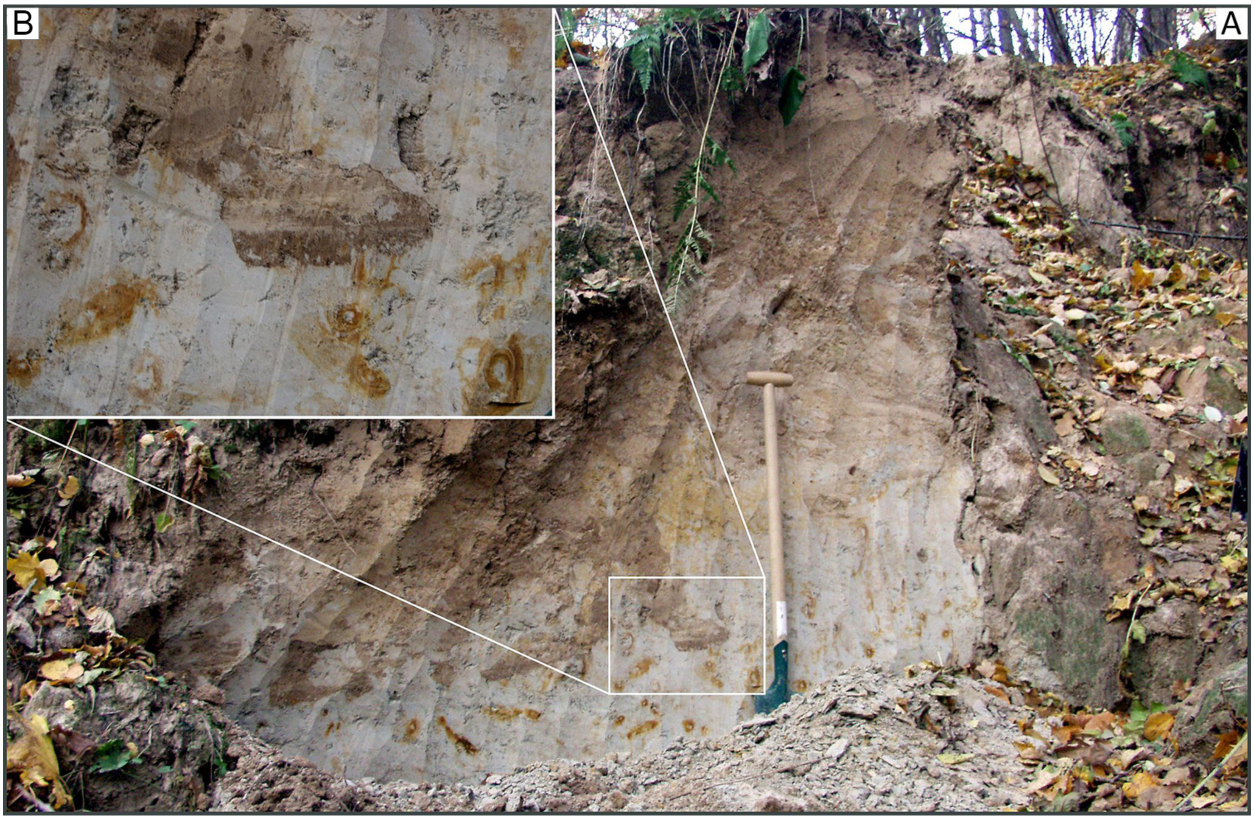

Fig. 10. Pipe filled up with sediments at the intermediate forest edge.

Fig. 11. Pattern of runoff along the recent forest edge on the agricultural terrace (A) and severe piping on the slope of the gully (B).

Discussion

Phases of piping

At the end of the modern erosional period, two phases of piping activity can be distinguished (Fig. 12). One, from the late nineteenth and early twentieth centuries, was associated with the parcelling out of part of the Celejów estate, the fragmentation of manorial land and changes in the pattern of fields (Kowalik-Bodzak 1964). The second, contemporary, a century later, is associated

Fig. 12. Dynamic development of the single Site 3 collapsed pipe: A – 2012, B – 2013, C – 2015, D – 2022.

Table 1. Reactivation of selected collapsed pipes in the gully system of Kolonia Celejów under the influence of runoff episodes from fruit plantations.

Collapsed pipe	Role in local system	Start	Reasons for activity		Volume in m^3 (approximately)			
			Initiation	Development	1999	2005, 2006	2009, 2013, 2015	2024
Site 1	Main form	1996, 1997	Longitudinal cultivation	New planted chokeberry	270* (1940)	106		240
	Secondary form	2006	As above New planted blackcurrant	Concentrated runoff from blackcurrant plantation	–	–	24 (2013) 36 (2015)	95
Site 2	Main form	1996, 1997	Diagonal cultivation	New planted blackcurrant plantation	85	186	?	240
	Secondary form	2006	Flow diversion	As above	–	27	50	114
Site 3	Main form	1996, 1997	Longitudinal cultivation New planted blackcurrant	Continuous blackcurrant seedlings plantation	45	?	?	912
Sites 1–3	Differentiated	1996–2006	New fruit plantation	Shrub rows parallel to slope	–	–	–	–

*approximate volume of waste in the reclaimed collapsed pipe at Site 1 before reactivation.

with berry bush plantations and cabbage cultivation (Rodzik, Zgłobicki 2000. Rodzik et al. 2009. Zgłobicki 2002). The development of three representative collapsed pipes demonstrates the spatial-temporal complexity of the transformation of these forms (Table 1), occurring under the influence of not only indirect, but also direct, intentional human intervention (Fig. 13).

The modern development of collapsed pipes was initiated by pronounced runoff after the long, cold and snowy winter of 1995/96. In the first days of April 1996, intense snowmelt triggered the development of numerous piping forms in the loess gullies of the western part of the Nałęczów Plateau (Gardziel, Rodzik 2005). In the gullies near Celejów, the effects of snowmelt were superimposed on the effects of heavy rainfall: in September 1997 and June 1999 (Zgłobicki 2002). The stages of contemporary collapsed pipes evolution are presented in the example of Site 1.The

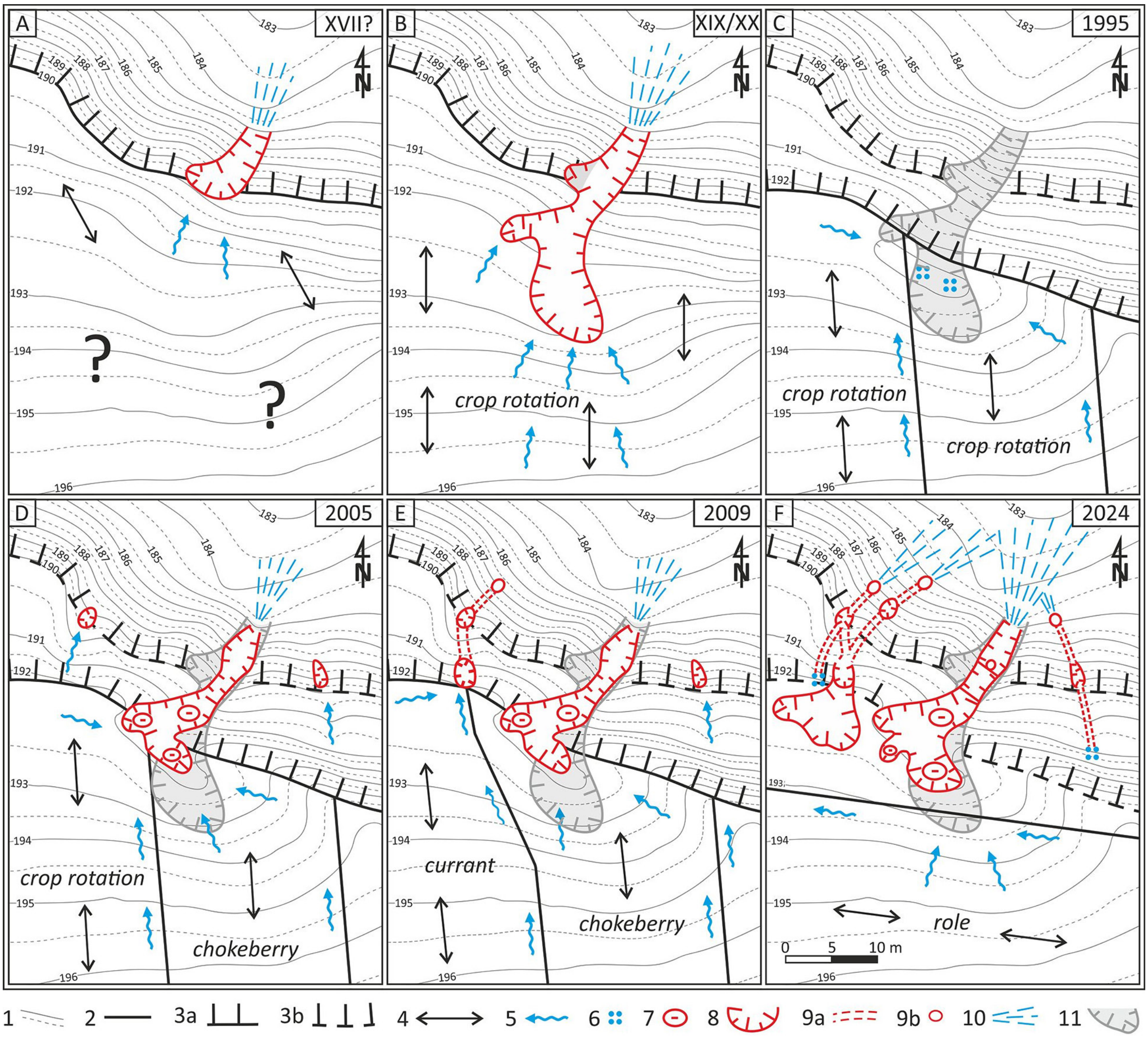

Fig. 13. Development phases of the Site 1 collapsed pipe: A – dissection of the young gully escarpment in axis of depression. B – development of the large collapsed pipe on the line of concentrated runoff after the change of cultivation direction. C – relocation of the forest edge and reclamation of the collapsed pipe. D – reactivation of the collapsed pipe under the chokeberry plantation. E – the beginning of the development of secondary collapsed pipes during the period of stabilization, F – Intensive development of secondary forms during periods of higher rainfall. Explanations: 1 – contour lines, 2 – parcel borders, 3 – forest edge, 3a – current, 3b – former, 4 – direction of cultivation, 5 – direction of surface runoff, 6 – increased infiltration, 7 – sinkhole, 8 – collapsed pipe, 9 – piping channel, 9a – subsurface, 9b – open, 10 – colluvial fan, 11- colluvial filling of the reclaimed collapsed pipe.

first few years of development (Fig. 13D), associated with frequent runoff, mainly from snowmelt, were followed by several years of stabilization of the forms (Fig. 13E), with low rainfall and retention in sodded plantations. In subsequent wet years, rainfall runoff was frequently recorded. Changing runoff from plantations to bypass existing collapsed pipes resulted in the development of secondary forms (Fig. 13F).

Impact of land use on piping

Our research confirmed that land use changes significantly affect soil piping through alteration in soil properties and surface and subsurface runoff (Table 2). Studies by Wilson et al. (2015) indicated that different land uses affect soil characteristics, intensive agriculture or pasture may increase the likelihood of pipe formation due to changes in soil structure and compaction. In particular, they emphasise the role of past land use, which has influenced changes in the morphology of the soil profiles and the formation of poorly permeable horizons. At the same time, research by Jones, Cottrell (2007) indicates that piping processes occur more frequently on agricultural land than in forests. The same conclusions were reached by Bernatek-Jakiel and Jakiel (2021) for areas located in the Bieszczady Mountains (Poland). In our case, intense piping developed at the forest edge, with form renewal often occurring at the boundary of in-situ loess and what colluvium fills the fossil sinkholes (Table 2). The way the land is used affects the volume of water flowing down the slope and can lead to the development of piping processes. Where there is a high hydraulic gradient near the edge of the gully, infiltration and piping develop.

Agriculture pressure on the gullies stopped in the 1970s, which had to do with the development of industry, providing employment – it was common to commute to work in city of Puławy. Access to building materials and fuel was easier. Gully channels were not needed for the passage of motor vehicles, and the plots of land located in them were not suitable for mechanized cultivation, so they were set aside. Agrotechnical services recommended the use of soil-stabilizing crops, such as orchard crops, which include fruit plantations. After the political transformation, since the 1990s, crops of brassicas and ornamental shrubs also appeared.

Piping and gully development

In the modern period, the layout of the manorial fields was dominated by extensive fields, oriented SSE–NNW, parallel to the southern gully. This field direction was preserved on the north-eastern edge of the catchment area (Fig. 2). It is likely that they stretched all the way to the present-day Kolonia Stok, crossing the dry valley,

Table 2. Determinants of the development of collapsed pipes on the gully bank as a result of agricultural activity.

Natural conditions and processes		Processes	Anthropogenic conditions and processes	
Moisture – high susceptibility of loess to erosion	Large slopes and denivelations – gravitational force	Snowmelts, downpours slope runoff	Tillage perpendicular to the contour	Cultivation of crops that do not cover soil sufficiently
Disintegration of aggregates	Creeping	Sheet and rill erosion	Tillage erosion	Splash, sheet and rill erosion
Effect – transport of soil material and accumulation in the form of an agricultural terrace at forest edge				
Flattening of the slope – infiltration	Threshold – increase in slope	Concentration of runoff along the edge	Ploughing up of small incisions	Creation of a new forest edge
Piping, channel widening	Increase in gravitational force	Headcut erosion, pipes	Vulnerability to erosion of agricultural colluvia	Visual increase in the depth of the gully
The result – the development of a collapsed pipe with a drainage channel and a depositional cone				
Soil slides on edges	Blocking the outflow and silting up the bottom	Collapsed pipe stabilization and infilling	Cutting off the edge of the collapsed pipe and backfill	Ploughing around the collapsed pipe
Effect – reclamation of the form – adaptation to agricultural use				
Piping, headcut erosion	Unblocking the drain, piping	Infiltration, piping	Reduction of inflow – development of secondary forms	Accelerated collapsed pipe development
The result – reactivation of the collapsed pipe				

which, along with them, was soon cut by the northern gully. This is evidenced, among other things, by the distribution of bank gullies of this gully every 100 meters, formed on the borders of the fields (Fig. 2). Contributing to their development were roads running across the gully. The profiles of fossil Luvisol and the relationship of the field pattern and gullies indicate the diametrically opposed ages of the two main arms of the gully system. The southern one was formed in the Neolithic, while the northern one was formed in the period corresponding to the ascending phase of the Little Ice Age (Rodzik et al. 2014).

The edges of permanent gullies are particularly threatened by piping and headcut erosion as a result of concentrated surface runoff from agricultural fields. A large role is played by the stabilization of the forest edge, usually functioning over the edge of the gully (Maruszczak 1954, 1973). In this zone, cracks are formed as a result of tension and agrotechnical operations, promoting water infiltration and subsurface runoff. Between the maximum extent of tillage and the forest edge, abandoned grassland or shrubs buffer strips are formed. These buffer strips are characterized by intense biological activity of burrowing soil fauna, promoting subsurface runoff (Verachtert et al. 2013, Wilson et al. 2015, Poesen 2018, Hosseinalizadeh et al. 2023). Additionally, the gully slope determines steep local hydraulic gradients. As a result, sinkholes and collapsed pipes starting to develop in these locations (Rodzik et al. 2021, Kołodyńska-Gawrysiak et al. 2024). Piping associated with a steep hydraulic gradient is mainly observed in earth banks: agricultural terraces, lynchets, sunken lane banks and gully banks (Poesen 1989, 2018, Verachtert et al. 2011, Vanmaercke et al. 2021). It is often initiated by small animal holes (Verachtert et al. 2010, 2011). The formation of piping sinkholes several meters in size and with a volume of up to 100 m^3, usually takes several years, but this can occur even during a single, intense snowmelt event. After some time, under the influence of changes in agricultural practices in the micro-catchment, the sinkholes and collapsed pipes may become not active, but remain "on standby" for further development under favourable conditions. The final stage of their development may be a blind valley, dissecting the edge of the gully or a bank gully (Gardziel et al. 1996. Rodzik, Zgłobicki 2000, Verachtert et al. 2010, 2011, Kołodyńska-Gawrysiak et al. 2024).

Piping processes thus contribute to the spatial development of gullies, especially during snowmelt (Gardziel, Rodzik 2005, Poesen et al. 2003, Vanmaercke et al. 2016). Episodic runoff outflows from animal channels usually do not exceed 1 $dm^3 s^{-1}$, but are significantly saturated with suspended solids, up to 200 g dm^{-3} and more. This is favoured by thawing of the ground and gravitational processes (drop-off and liquefaction) on the pipe walls. Saturation with suspended sediments forces its deposition (usually on snow) at the slope drop-offs at the outlets of the passages in the gully bottom (Rodzik et al. 2009). The result is the relative stabilization of such a section of gully with a flat, accumulative bottom.

The stabilization of the bottom slopes was an incentive for owners of small farms to enlarge them by putting such a section of the gully under short-term cropland. This was preceded by hand clearing of trees and shrubs. This involved smoothing of the slopes by gravitational displacement of soil activated by tools. However, fields that were difficult to cultivate were soon turned into pastures and eventually into fallow land, subject to a secondary succession of Tilio-carpinetum forest with pioneer birch (Rodzik 2010). The loosening of the loess subsoil and poor consolidation of the infilled incisions from the first phase, created conditions for the re-development of sinkholes, collapsed pipes and channels, as exemplified by the three selected sites on the edges of the loess gully in the Kolonia Celejów on the Nałęczów Plateau.

Conclusions

Land use and its changes had a big impact on the creation and reactivation of fossil piping forms. This affects the volume of water reaching the edge of the gully and also the characteristics of the soil and sediment cover present at the forest edge. Piping is favoured by young plantations of fruit bushes, which can generate significant surface runoff in the early stages of cultivation.

Nowadays, piping erosion is the main process causing the spatial development of loess gullies – i.e. an increase in their area. This process degrades, mainly during rainfall runoff, the step on the slope (forest edge) formed over the edge of the gully. Layout of berry bushes rows perpendicular to the contour lines favours overland and subsurface flow. The long-lasting concentration of runoff results in the rapid development of a single, large form and, consequently, a bank gully. Separation of runoff usually leads to the development of new (secondary) piping forms.

Piping is an important link in the transport of soil and sediments from slopes to the bottom of gullies. Deposition of material transported by tillage and sheet erosion occurs at the forest edge. Once formed, it acts as an alimentation zone for piping, transporting material to the bottom of the gully, where it is mostly deposited.

The development of collapsed pipes is unequivocally influenced by unintentional agricultural activity. It creates the conditions for the development of piping by directing and concentrating slope runoff and weakening the soil structure. Man interacts with piping through such elements of the agrarian structure as the perpendicular arrangement of fields to the contour lines, the formation of an agricultural terraces at the forest edge, and the plowing of the slopes of the gully.

Intentional activity is mainly the infilling of collapsed pipes with various waste materials, mostly vegetal, such as weeds, branches and grubby fruit bushes. A special type of intentional activity is the adaptation of piping forms to agro-vegetable production by backfilling and consistent plowing. Such reclamation usually turns out to be impermanent and leads to reactivation of fossil forms.

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Author's contribution

J.R. – conceptualization; J.R., R.K.-G., Ł.F., W.Z. – investigation; J.R. – methodology; J.R., J.P. – supervision; J.R., Ł.F. – visualization; J.R., R.K.-G., Ł.F., W.Z., J.P. – writing – original draft; J.R., R.K.-G., W.Z. – writing – review & editing.

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