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Morphological and geochemical record of historical erosion on the example of small alluvial and deluvial fans accumulated on the Bug River terraces in the Neple area (Podlasie Lowland, eastern Poland)

Piotr Szwarczewski, Anna Rogóż-Matyszczak, Łukasz Zbucki

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Abstract. The gullies in the vicinity of Neple (Podlaska Lowland, eastern Poland) are relatively young and were created due to the land use and climate changes. The aim of the research was to determine the variability of selected alluvial-deluvial fans occurring in the Bug River valley and their age using interdisciplinary methods (e.g. absolute dating, geochemical analyzes, cartographic data). Geological mapping and several drillings (both within the fans, valleys or gullies bottoms and glacial or fluvioglacial plateaus) were done. Historical data dealing with the human economic activity in the region were analyzed. The obtained radiocarbon dating and geochemical features of sediments building the alluvial and deluvial fans proved that these forms are not older than some 500 years. Due to the lateral movement of the Bug River channel only some of the forms are preserved in the area under study. The rest of them disappeared due to the fluvial erosion.

Keywords: *human impact; trace elements; land use changes; gully erosion; radiocarbon dating*

✉ *Piotr Szwarczewski (pfszwarc@uw.edu.pl), Faculty of Geography and Regional Studies, University of Warsaw, Krakowskie Przedmieście 30, 00-927 Warsaw, Anna Rogóż-Matyszczak (a.rogoz@pswbp.pl), Łukasz Zbucki (zbuckilukasz@op.pl) Pope John Paul II State School of Higher Education, Sidorska 95/97, 21-500 Biała Podlaska*

INTRODUCTION

Alluvial and deluvial fans formed at the mouth of erosional cuts (e.g. gullies, dry valleys) can be treated as a unique archive that records historical and prehistoric erosion phases caused by both climate change and the economic activity of humans (e.g. Starkel 1988, 1989, 2005; Bork 1989, Maruszczak 1991; Nowaczyk 1991; Sinkiewicz 1993, 1998; Klimek 2002; Dotterweich *et al.* 2003, 2014; Smolska 2005, 2007; Twardy 2008; Szpikowski 2010; Kappler *et al.* 2018). Various deposits accumulated due to the erosion in fans are a source of information about environmental changes that took place in the catchment areas of the analyzed forms in the period of their formation and evolution (e.g. Bork 1989; Nowaczyk 1991; Borówka 1992; Sinkiewicz 1993, 1998; Klimek 2002; Zolitschka *et al.* 2003; Smolska 2005, 2007, 2012; Kalicki 2006; Szwarczewski 2009b; Hildebrandt-Radke 2010; Dreibrodt et al. 2010, 2010; Kappler *et al.* 2018). The gullies are often formed in the edge zones of moraine uplands and on the slopes of river valleys. The formation of erosive cuts depends on geological factors, geomorphology (slope length and inclination), vegetation cover as well as weather conditions and human economic activity. The areas built of boulder clays, loess or other deposits containing significant amounts of silt-clay fraction are very prone to formation of cuts and development of gullies. Locally, their number and density can be so large that it hinders the functioning of settlements and the everyday life of the local population. There are many studies presenting the relationship between economic, prehistoric and historical, human activity and the development of erosional forms (gullies and ravines). These papers analyze variability of grain size, sedimentological indexes, as well as the erosion/accumulation rates and their relation to specific historical phases of anthropogenic impact based on historical and archaeological data and absolute dating of sediments (e.g. Nowaczyk 1991; Sinkiewicz 1993, 1998; Klimek 2002; Lang 2003; Stankoviansky 2003; Smolska 2005, 2007, Szwarczewski 2005, 2009a, b; Zgłobicki 2008; Smetanova *et al.* 2017).

Studies of this type include both individual case studies and regional elaborations presenting the subsequent stages of the economic use of the area and its geomorphological effects (Nowaczyk 1991; Sinkiewicz 1993, 1998; Klimek 2002; Smolska 2005, 2007, 2012; Zgłobicki 2008, Dreibrodt *et al*. 2010; Kappler *et al.* 2018). The research in the areas where erosional cuts develop in the vicinity of active river channels, e.g. the Vistula valley near Zakroczym or Wyszogród (Wasilewska 2009) or in the Bug valley at the level of the mouth of the Krzna – around the town of Neple (Rodzik *et al.* 2004, 2014), prove to be extremely difficult. The lateral migration of large river channels destroys the accumulated fans or let them exist in a reduced form. Very often we are dealing with the incorporation of the sediments building these forms into the river transport as a result of lateral erosion or alluvial-deluvial fans are not created because the material originating from gully erosion is deposited directly into waters of the active river channel. There are also such situations when the alluvial-deluvial fan is only partially preserved as a gently inclined surface at a side of the valley. Dating of such accumulation forms is possible only when the fan sediments cover the older organic sediments (e.g. peat, mineral-organic silt, fossil soil), when the fan sediments cover the morphological level used in the past by man, with numerous artifacts allowing to determine the absolute age or when the forms are very young and we have available detailed, archival and historical cartographic data.

The main aim of the research was to determine the sedimentological and geochemical variability of selected alluvial-deluvial fans occurring in the Bug River valley near the town of Neple and their age using various methods such as absolute dating or analysis of available archival cartographic materials. These accumulation forms were created at the mouth of gullies cutting both higher river terraces or glacial plateau. The sites for detailed research were selected on the basis of analysis of lateral river channel changes observed on available topographic maps and after the geomorphological mapping done in autumn 2016 and spring/summer 2017.

The analysis of archival and contemporary topographic maps of the Bug River valley (and adjacent areas) in the studied section showed a significant number of such erosive forms, often ending near the modern channel. Only a few of them had preserved accumulation fans at the mouths of gullies, most of them disappeared due to the lateral migration of the river channel (Figs 1, 2).

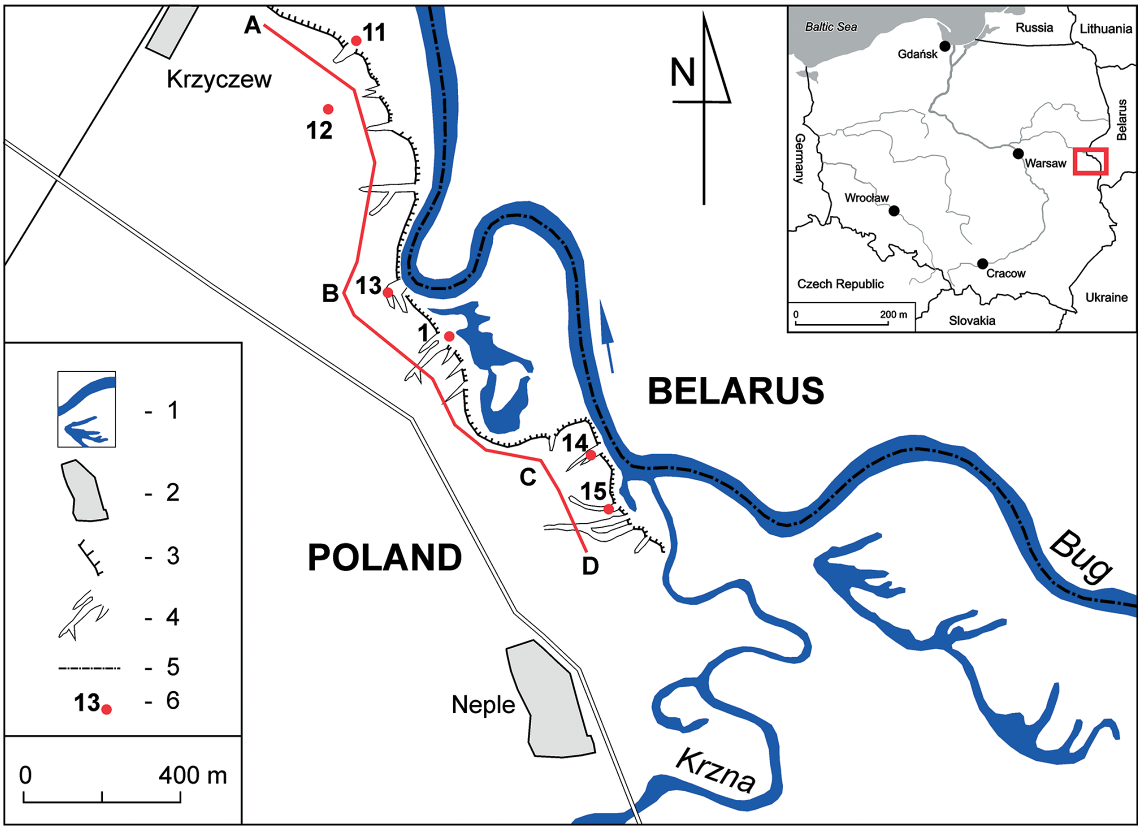

Fig. 1 Location of the study area. 1 – rivers and oxbow lakes, 2 – towns, settlements, 3 – valley edge, 4 – gullies, 5 – country border, 6 – boreholes/sampling sites. A-B-C-D – line of geological cross-section

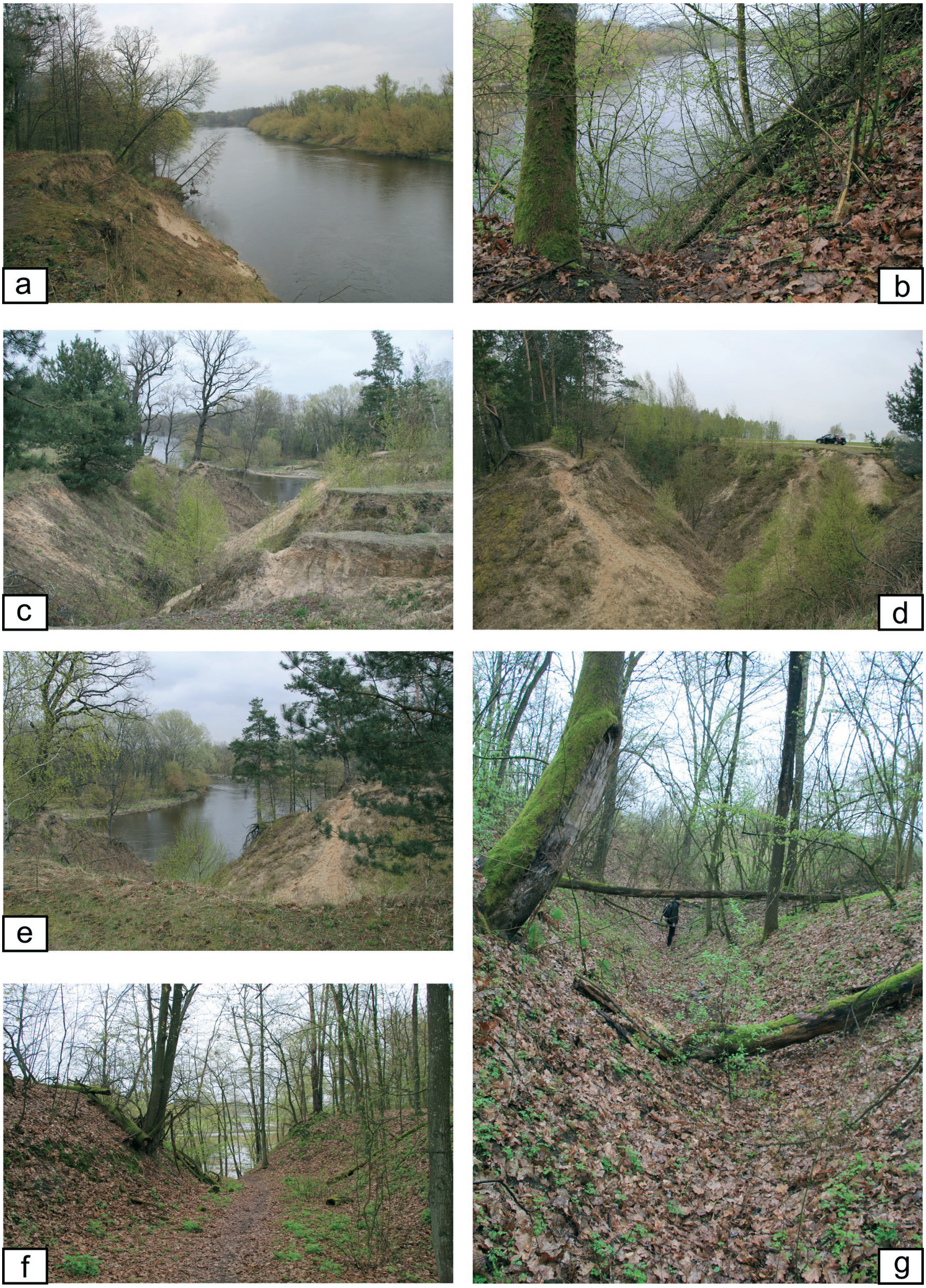

Fig. 2 Gullies in the Neple 1 (a–d) and Neple 15 (e–g) vicinities

The studies carried out so far in this area (Rodzik *et al.* 2004, 2014) indicate that sediments that build the slopes of the Bug valley are very susceptible to erosional processes. An extreme rainfall event in 2002 led to the creation of an initial form (75 m long, 10–20 m wide and 5–10 deep), which after subsequent downpours became bigger and deeper (Rodzik *et al.* 2004). The agricultural use of the plateau and the geological structure adjacent to the edge of the valley favours the development and deepening of these contemporary erosion forms.

METHODS

Interdisciplinary research methods were used in this study. They included geological and geomorphological mapping, archival and contemporary topographical maps analysis and sedimentological and geochemical analyses of the deposits building the alluvial-deluvial fans, river terraces and moraine plateau surfaces. The age of organic sediments covered by the deposits from gully erosion was established by radiocarbon dating. Organic matter content was assessed with the use of loss on ignition method (4 hours, 550°C), and mineral composition of the samples was done with the use of an optic microscope (Zeiss Axioscope).

The samples used for geochemical analyses were dried at 105°C and then sieved with the use of a 0.063 mm nylon sieve. A mixture of HNO_3 and HCl concentrated acids (aqua regia) was used for the extraction in a microwave digestive system. Concentration of elements (Fe, Mn, P, Cu, Pb and Zn) in the sediments was determined by the ICP OES method. This set of elements was chosen for research because it reflects well the occurring natural changes, e.g. fluctuations in the water level (Fe, Mn) as well as the occurring human impact (P, Cu, Pb and Zn). Electron microscopic (SEM) observations have been made with HITACHI TM3000 with an energy dispersive spectrometer (EDS) SWIFT ED 3000 Oxford Instruments.

SEM EDS and the physicochemical analyses of the samples were performed at the Regional Research Centre for Environment, Agricultural and Innovative Technologies EKO-AGRO-TECH, Pope John II State School of Higher Education in Biała Podlaska and University of Warsaw laboratories. In total, over 100 samples have been subjected to various analyzes.

Area of the study

The area of research is located on the western edge of the Bug River valley, which is the border between Poland and Belarus (Fig. 1). The contemporary relief of the studied area was created during the Odra-Warta glaciations period, in the periglacial conditions of the Vistula glaciation and in the Holocene (Nitychoruk *et al*. 2003, 2007, 2018). The changing climate and the repeated transgressions of the ice sheets, with stagnation and recessionary phases led to the formation of a lowland moraine plateau that was fragmented with river valleys and cut with dry valleys. The contemporary landscape is the result of complex geomorphological processes that took place during the last 15,000 years. During the Pleistocene period, four levels of glacial tills were accumulated. These sediments are separated by lacustrine, fluvioglacial and fluvial sediments. The thickness of individual till levels usually does not exceed 10–20 m, and deposits associated with the San 1, San 2 and Odra glaciations can reach 20–30 m thickness in total. In the Bug and Krzna valleys and on the adjacent upland there are fluvioglacial and fluvial sediments, the total thickness of which may exceed 15 m. Sands and silts dominate in terms of fraction, but gravel sediments also occur in the deposits (Nitychoruk *et al.* 2003, 2007, 2018). The geological structure of the studied area in a synthetic form is shown in Fig. 3. On these fine-grained sands and muddy clay deposits occurring on the surface, the gullies have developed.

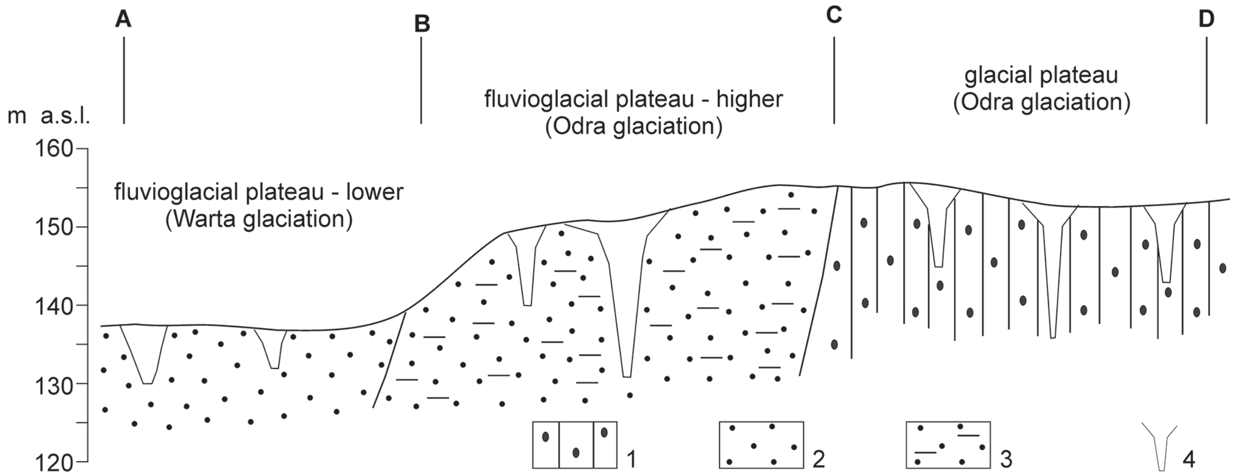

Fig. 3 Simplified geological cross-section (on the basis of geological map by Nitychoruk et al. 2003). Location of the profile indicated on Fig. 1. 1 – glacial till (Odra glaciation), 2 – fluvioglacial deposits: sands, sands and gravels (Odra glaciation), 3 – fluvioglacial deposits: sands, sands with gravels and muds (Warta glaciation), 4 – gully

From the geomorphological point of view two types of landscape can be distinguished: autonomous areas, i.e. the morainic plateau with dead ice moraines and higher morphological levels of glaciofluvial origin, and the subordinate areas represented by floodplains and overbank terraces. The autonomous areas as well as levels in bottoms of valleys are varied by aeolian forms of various sizes. During the field mapping, the authors noted a fairly large eolization of sediments occurring in the surface deposits building the upland and higher terraces.

The morainic edge zone under study is characterized by various slope steepnesses. The sections cut by the Bug River channel (today or in the past) have steep slopes exceeding 30° (southern part, Fig. 1), while in the vicinity of Krzyczew the plateau is slightly lower and falls down by a gentle slope inclined at several degrees. The gullies in the northern part are created in the bottoms of dry valleys ending in the Bug River valley (Figs 1–4).

Although the research area was penetrated by humans already in prehistory (stone age) but its activity did not leave major changes in the natural environment. Permanent and constant settlement began in the Middle Ages with the appearance of the Slavs (around the 10th century). Significant deforestation increases in the number of villages and areas used for agriculture in the studied area have been noted since the time of the Polish-Lithuanian Union (14th century) and especially from the 16th century (Bienia 2003; Wetoszka 2003).

RESULTS AND DISCUSSION

The analysis of available archival topographic maps (covering the period from the end of the 18th century to modern times) recording information such as changes in land use and the course of major communication routes indicates that at the turn of the 18th and 19th centuries, several active erosional forms (gullies?) existed in the area under study. They were formed in the bottoms of dry valleys ending their course in the edge zone of the Bug River valley. Their creation was associated mainly with the functioning of local dirt roads connecting the plateau with the agricultural bottom of the valley (Figs 1, 2).

The gullies formed due to the linear erosion had to develop rather quickly and were a great difficulty for the local population because subsequent editions of archival topographic maps show the abandonment of the use of these forms. The forms were immediately colonized by vegetation (bushes and trees) since the roads were not in use. On map editions from the first half of the 20th century, many gullies are marked as stabilized by vegetation (forests and bushes). The lateral migration of the channel and its approximation to the western part of the valley also had some influence on the cessation of the use of these roads (road gullies). The migration of the river channel and more frequent flooding of the eastern part of the valley contributed to the temporary abandonment of agricultural use of this part of the Bug River valley.

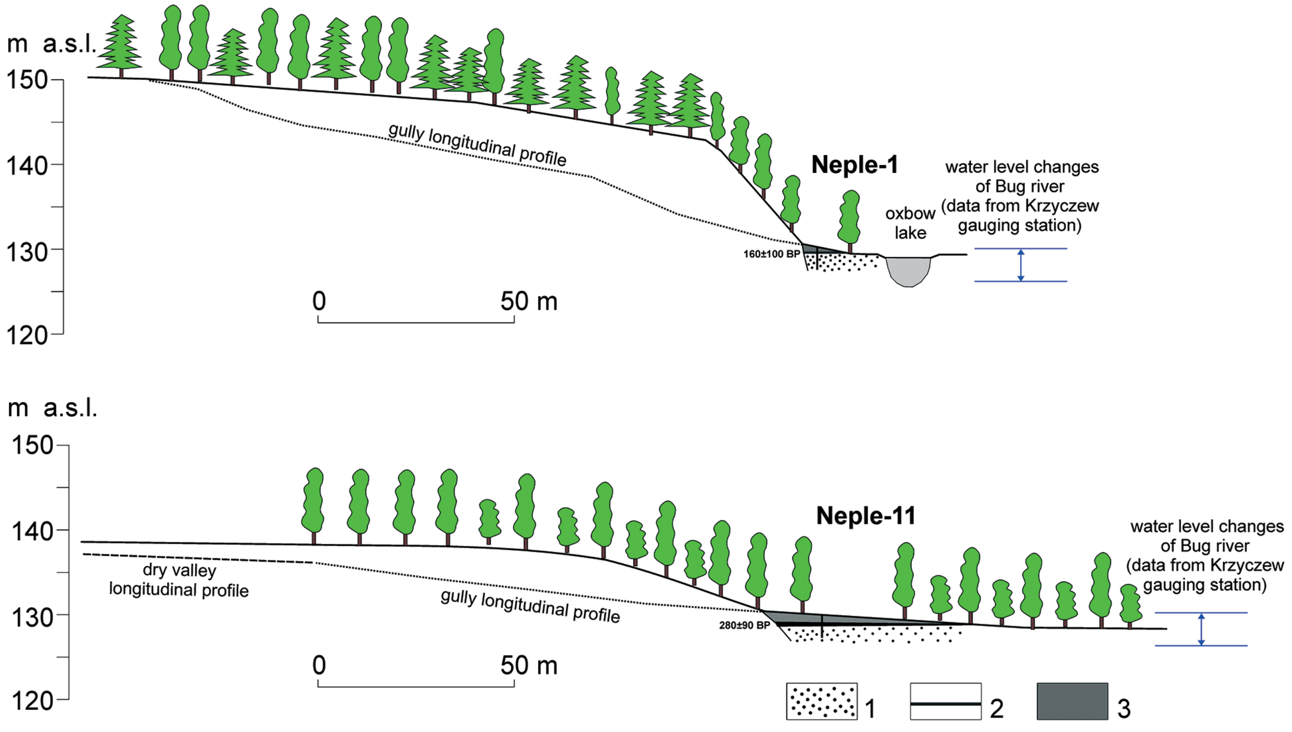

Fig. 4 Geomorphological profiles of the Bug River valley edge in sites Neple 1 (top) and Neple 11 (bottom). 1 – alluvial sands and muds, 2 – buried organic horizons, 3 – deposits building the alluvial-deluvial fans. Borehole (sampling site) is marked by vertical dash; the age of buried organic horizon is indicated in uncalibrated ^{14}C years (more detailed results of radiocarbon dating are presented in Table 1)

The research carried out as part of the monitoring within the *Szwajcaria Podlaska* reserve (Rodzik *et al*. 2004, 2014) indicates that the sediments building the fluvioglacial plateaus and upland are very susceptible to linear erosion processes. It is resulted mainly due to the grain size composition of sediments occurring on the surface (large proportion of fine sands and dust, sometimes exceeding 50%). The rate of incision process is very big, what is illustrated by the attached photos (Fig. 2, a–c) and it is favoured by the agricultural use of moraine plateau and glaciofluvial plains.

The lithological diversity of analyzed profiles is shown in Figs 1, 3, and 4. In terms of origin, several main different facies (types of sediments) can be distinguished: (1) glacial and glaciofluvial (profile Neple 12) built of silts/muds and fine sands with single gravels in the bottom, (2) fluvial, channel deposits consisting of fine and medium-grained sands and occurring at the bottom of the Bug River valley (profiles Neple 1 and 11), (3) fluvial, overbank deposits consisting of silts/muds with fine sands and dispersed organic matter (profiles Neple 1 and 11), and (4) diversified in grain size, deluvial and proluvial sediments building the fans and accumulating within the erosional cuts (profiles Neple 1, 11, 13, and 15).

In terms of mineralogy, the analyzed sediments consist predominantly of quartz grains of sand and dust fraction (Fig. 5) with some clay minerals and various content of differentiated organic matter – from homogeneous, amorphous organic matter, detritus preserved in various forms to wood charcoals.

During the collection of samples in the field there was determined pH (in KCl, by Hellig colorimetric method) for all main genetic levels. The samples, re-

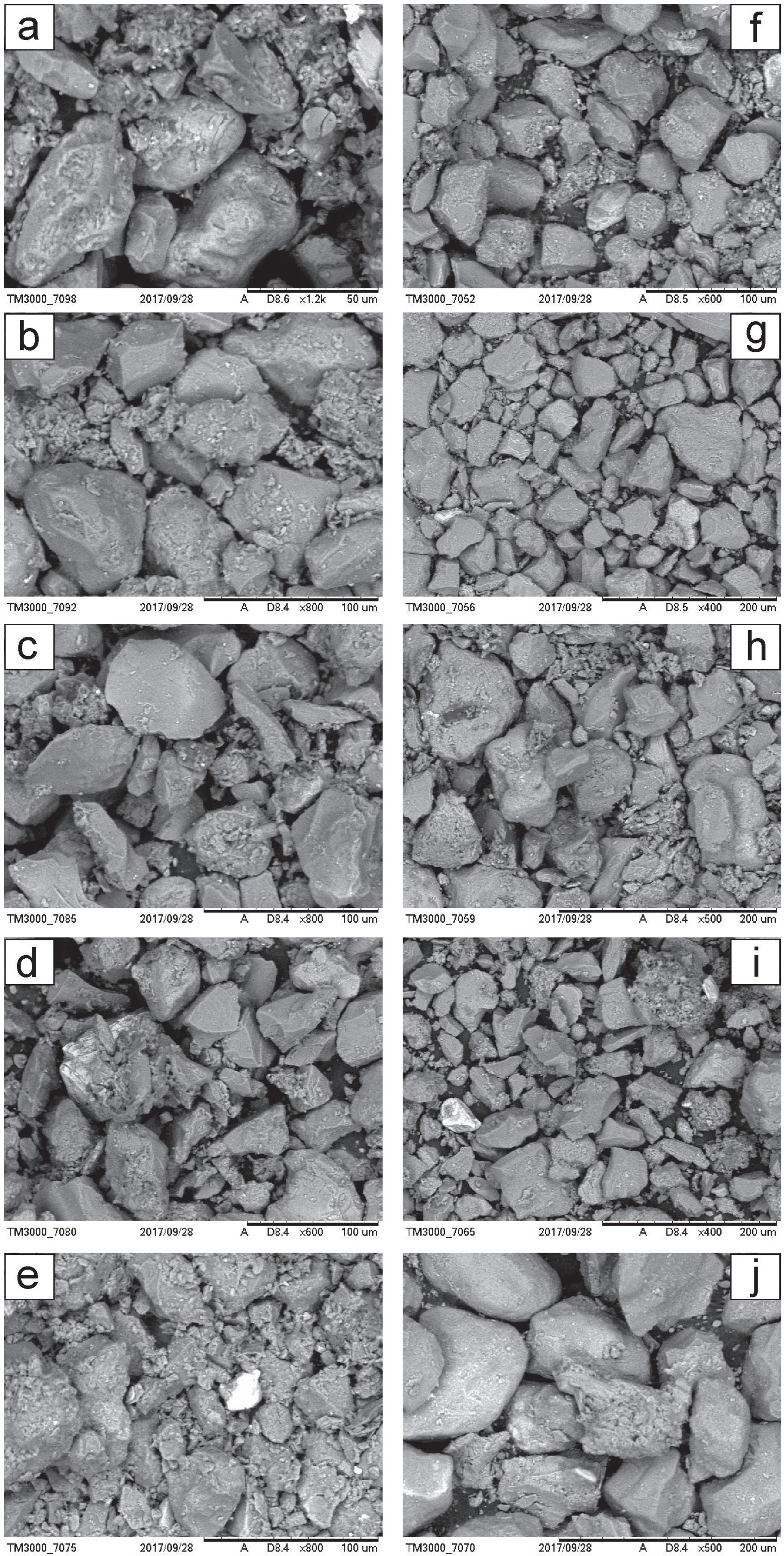

Fig. 5 SEM images of the samples from Neple area profiles: Neple 11 – a (0–20 cm), b (90–100 cm), c (147–155 cm), d (165–170 cm), e (200–210 cm); Neple 12 – f (0–15 cm), g (80–100 cm); Neple 15 – h (0–20 cm), i (40–60 cm), j (180–200 cm)

gardless of the grain size and origin, had similar neutral to alkaline pH (namely, from 6.0 to 7.5 pH), what favours the sorption of heavy metals in the deposits. Their accumulation is also favoured by the organic matter dispersed in the mineral deposits and carbonates occurring in various forms.

Radiocarbon dating of 3 profiles (Neple 1, Neple 11 and Neple 14, Figs 1 and 4, Table 1) indicates that the process of deposition within the erosive part of gullies (or valley) bottoms and alluvial-deluvial fans started relatively recently – at the earliest, about 200–500 years ago what allows for the assumption that the youngest phase of evolution of these erosional forms and in some cases the beginning of their creation is related with the development of intensive settlement and agricultural activity in this area, i.e. 14th–16th centuries (Bienia 2003; Wetoszka 2003). The establishment of new settlements was accompanied by deforestation and development of agricultural activity. The increase in the economic activity of the local residents in the studied area is confirmed by the facies changes in the sediments that build the fans, by the increase in the mineral matter content, often with a thicker fraction, and in the content of trace elements, the amount of which increases in the youngest (top) part of the alluvial-deluvial fans.

The chemical composition of sediments that build the glacial plateau, alluvial-deluvial fans or filling of dry valleys or gullies bottoms depends on many factors, including, among others, geological structure, grain size composition, intensity of hypergenic processes, pH, redox, or anthropo-pressure, i.e. human economic activity changes in the historical past (e.g. Zgłobicki 2008; Szwarczewski 2009b).

A good mutual correlation of analyzed elements (see Table S1 in Supplements) in the studied profiles indicates that they come from the same (or similar) origin, i.e. anthropogenic "supply". The higher contents of Cu, Pb and Zn are associated with the last period of human activity in the study area. The date of increase is also confirmed by the obtained results of radiocarbon dating (Table 1).

In some borehole's sections there were observed considerable irregularities in variation of the concentration of the analyzed elements (Fig. 6, a–e). It may indicate that during the creation of the studied alluvial-deluvial fans or filling of the gullies bottoms there were some periodic interruptions in the supply of material and that the analyzed geological profiles recorded supply from two genetically different sources, i.e. (1) wet and dry deposition from air and supply from surface runoff (slopes) and (2) polluted floodwaters of the Bug River. Fluctuations in water level changes exceed 3.7 m in this area (Hydrological Review of the Year, 1950–1981).

The sediments accumulated in the vicinity of the Bug River channel are characterized by a significant vertical variability of the content of accumulated elements which is associated, in the opinion of authors, with the "mixed" supply of contaminated deposits from the soil erosion (local) and from the floodwaters. The deposits building the alluvial-deluvial fan located in the northern part of the studied area (Figs 1, 3, 6, 1–5) are characterized by a different type of variability in the contents of the analyzed metals. In the period before the fan was

Table 1 Results of radiocarbon dating. Calibration by OxCal v.4.2.3 Bronk Ramsey (2013), r5 IntCal13 atmospheric curve (Reimer *et al.* 2013)

Sample name (depth)	Laboratory No.	^{14}C age (yr BP)	Calibrate age ranges (cal AD)	Dated material
Neple 1 (0.72–0.78 m)	MKL-3364	160 ± 100	68.2% probability 1665–1707 (12.4%) 1719–1820 (29.3%) 1833–1883 (14.3%) 1914 – present (12.2%) 95.4% probability 1521–1592 (6.3%) 1620 – present (89.1%)	buried organic horizon
Neple 11 (1.50–1.60 m)	MKL-3460	280 ± 90	68.2% probability 1473–1670 (12.4%) 1780–1799 (5.1%) 1944 – present (2.4%) 95.4% probability 1440–1699 (69.9%) 1721–1818 (16.2%) 1833–1880 (3.4%) 1916 – present (5.9%)	buried organic horizon
Neple 14 (0.56–0.70 m)	MKL-3461	30 ± 90	68.2% probability 1695–1727 (17.2%) 1813–1862 (21.0%) 1867–1919 (30.1%) 95.4 probability 1677–1765 (29.7%) 1773–1777 (0.5%) 1800–1940 (65.1%)	buried organic horizon

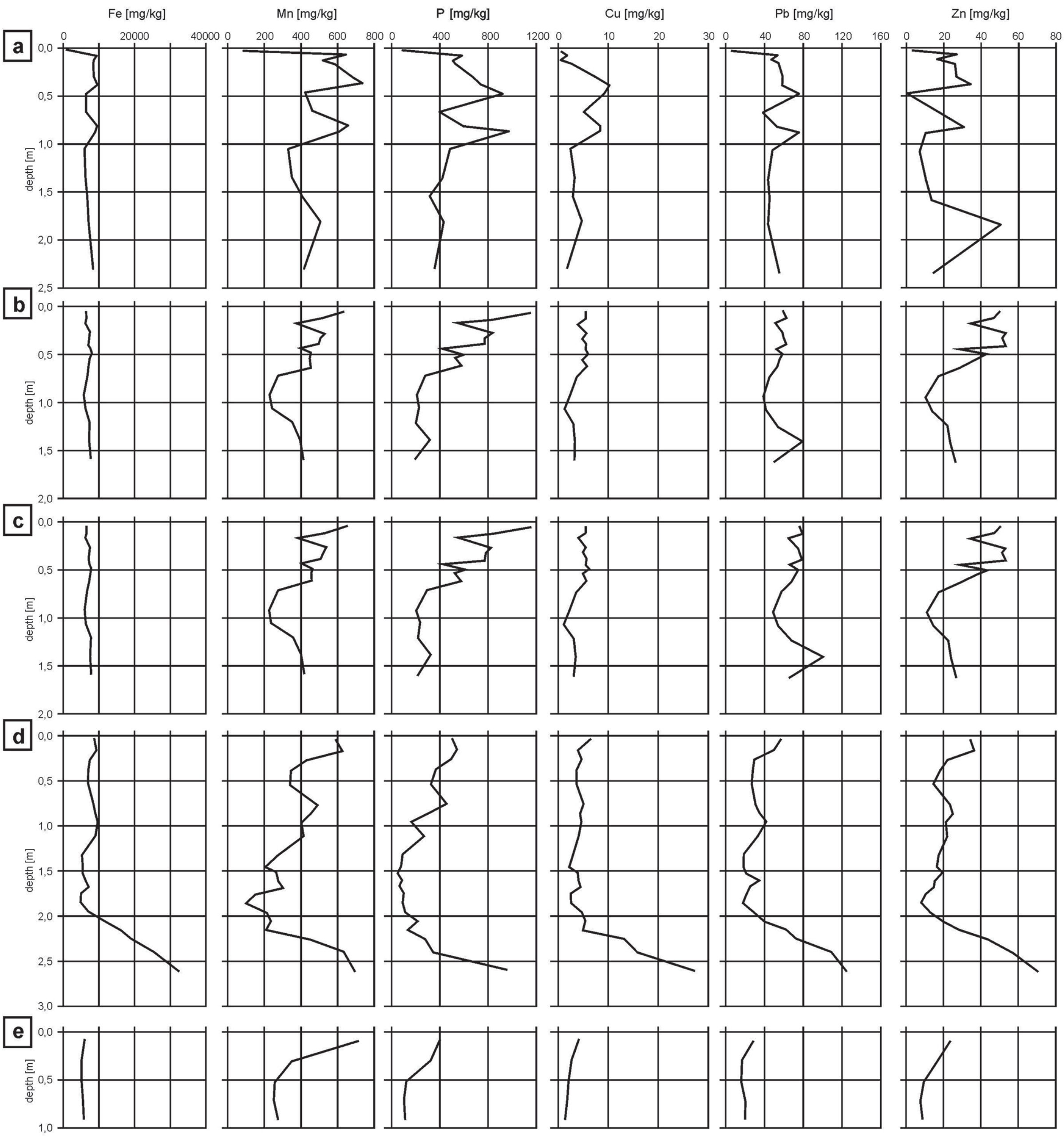

Fig. 6 Content of selected chemical elements in the samples from profiles: a – Neple 1, b – Neple 11, c – Neple 12, d – Neple 13, e – Neple 14

formed, when the river channel laterally shifted to the east and the extent and influence of flood waters were less frequent, there was observed a decrease in the content of trace elements with the depth (Fig. 6, a; Neple 11 profile). When a quite intensively used road appears in the dry valley bottom, a gully starts to form. In the bottom of the gully the sediments originating from slope erosion in the local catchment are transported, and at the gully mouth the alluvial-deluvial fan is created. The human economic activity gains strength and sediments moving along with the water flowing on the slope are more and more polluted due to the intensification of agriculture and increasing mechanization (e.g. fertilizers, herbicides, pesticides, fuels). This period represents an almost linear increasing content of all of the analyzed elements, i.e. Fe, Mn, P, Cu, Pb and Zn (Fig. 6, a–e). The sediments from the autonomous, almost flat areas, where no water erosion processes were observed, were affected only by the vertical supply of dry (due to the gravity) or wet (from the rainfall) pollution. There is observed a steady decline in the concentrations of the studied elements along with the depth (Fig. 6, c; profile Neple 12). The rate of erosional processes within the gullies and the size of accumulation cones in the area of the study are similar to those observed in other regions of Poland or Central Europe with the old glacial relief. They are slightly slower and smaller than those occurring in areas built from loess deposits (e.g. Smolska 2007; Dotterweich 2008; Szwarczewski 2009b; Dreibrodt *et al.* 2010; Piech *et al*. 2018).

CONCLUSIONS

A detailed field research in the vicinity of the town of Neple and the laboratory analyses of deposits allow the authors to draw the following conclusions:

1. Higher contents of selected chemical elements in sediments building alluvial-deluvial fans and filling the abandoned river channel or building old meander bars come from two main sources, i.e. (a) atmospheric delivery and surface runoff and (b) decanting of the Bug River flood waters.

2. The gullies cutting the moraine plateau and fluvioglacial levels are very young forms and are associated with changes in land use after the beginning of agricultural use of these areas by man. This is confirmed both by the absolute age of the sediments determined by the radiocarbon dating from the 14th–16th centuries to modern times (what is in concordance with the known history of development of this area) and by a strong mutual correlation of the concentration of selected chemical elements in the sediments that build the alluvial-deluvial fans and the upper part of the plateau. The humid and cold periods of the Little Ice Age with a higher frequency of extreme events could also have the impact on the development of these erosional forms.

3. A high erosional susceptibility of sediments building the moraine plateau and Bug River valley edge favour the creation of gullies and their rapid development. The obtained results are well correlated with ongoing monitoring studies.

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Table S1