Landform Analysis, Vol. 17: 183–192 (2011)

Development and morphology of gullies in the river Daugava Valley, South-Eastern Latvia

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Abstract: In south-eastern Latvia many old gullies can be found, however, few studies hitherto have reported on their morphology and factors controlling their genesis. This paper presents results of the research covering morphometry, morphology and classification of gullies, the paleogeographic reconstruction of environmental conditions and factors that led to development of these erosion landforms in the river Daugava Valley. Obtained results permits to distinguish five morphogenetic types of gullies, which differ by topographic characteristics, shape of cross-profile, time of formation, and genesis. Simultaneously, presence of different types of gullies in the case study area geomorphologically reflects several incision–accumulation cycles of the erosion network development.

Keywords: morphogenetic classification; gully types; south-eastern Latvia

Introduction

Climate change induced seasonal variations in amount and intensity of precipitation already are taking place in the Baltic Sea region. Moreover, according to regional modelling-based assessment of climate change, in the northern and north-eastern Europe annual precipitation could increase by 1–2% per decade, simultaneously return periods of extreme rainfall events could shorten (Impacts of Europe's changing climate 2004). Recent analysis of the expected climate change applying the A2 scenario for time period 2071–2100 in Latvia given by the BACC Author Team (2008) shows an increase of annual precipitation by 5–10% and mean annual temperature by 4–5°C. Local model developed by Latvian scientists (Sennikovs et al. 2008, Bethers & Sennikovs 2009), also forecasts shortening of winter period from 4 to 2 months, rising of mean temperature and increasing of mean monthly rainfall intensity during summer in south-eastern part of Latvia, where studies of gullies discussed in this paper were carried out. Such changes can cause more frequent occurrence of heavy rainfalls, formation of overland flow and intensification of fluvial erosion in this territory.

In its turn, the expected geomorphological consequences of these environmental changes will be the reactivation of accelerated erosion by water and rearranging of recent equilibrium of erosion and accumulation processes in headwater catchments of the Daugava River valley within the territory under study (Soms 2010). Taking into account that the main drainage elements of these headwater catchments are gullies of different size and types, renewing of downcutting in old gullies and formation of new ones could be anticipated.

Hence it is obvious the necessity for monitoring and geomorphological studies of existing gullies in context of modelling the effects of climatic changes on reactivation of erosion in old, inactive gullies. These landforms, which developed during the previous erosion cycles in this area, also provide relevant paleogeographic information about triggering and controlling factors of their formation and the time, when it occurred (Nachtergaele et al. 2002a, Zgłobicki et al. 2003, Vanwalleghem et al. 2003, Dotterweich 2005, Vanwalleghem et al. 2005a, Dotterweich 2008).

However, it is difficult to elucidate the individual role of climatic and human influence on formation of gully network in the Daugava river valley, despite the remarkable knowledge about gullies and gully erosion in general as well in historical context, aggregated from many studies realised in Europe and throughout the world during the last decade. First of all such difficulties result from fact that the initialisation and further development of the gully erosion network depends on many local factors and varies in regions with different landscape, climate and landuse (Poesen et al. 2003, Valentin et al. 2005), hence thresholds and controlling factors documented e.g. in loess belt of Western Europe not always are valid in regions with glacial till derived soils. Secondly, as it is noted by Panin et al. (2009), little is known about the Late Pleistocene and Holocene erosion chronology and its driving factors in Eastern Europe. Particularly this is an urgent problem in the coniferous and mixed forest zone of the western part of the East European Plain, including Latvia, where there is a lack of available scientific data about historical gully erosion. In south-eastern Latvia, where actual soil erosion risk is evaluated as very low (Kirkby et al. 2004), many old gullies can be found, but only some studies hitherto have reported factors controlling their genesis and regularities of spatial distribution (Soms 1999, 2006).

In order to get insight into these issues and to elucidate the origin of gully erosion network in a case study area in the Daugava river valley, detailed studies of permanent gullies and sediments linked to gully erosion were performed. The specific objectives of the study discussed herein were (1) to obtain *in situ* data on the morphometric and the morphological characteristics of permanent gullies, (2) to distinguish the different types of gullies considering their geomorphology and possible mechanism of formation, (3) to reconstruct the factors that led to their development and (4) to evaluate the ages of gulling events taking into account paleogeographic development of the valley and settlement history of the area.

Study area

The case study area is located in the western part of the East European Plain, in south-eastern part of Latvia, about 6 km east of Daugavpils, within the Daugava river valley stretch from Kraslava City down to Naujene village (Fig. 1A). With respect to physiogeographic division of Latvia, the study area belongs to Augšdaugava (Upper Daugava) Depression, where the Daugava (Zapadnaja Dvina), which is among the largest rivers in Eastern Europe, in its course from the Polatsk Lowland in east to the Eastern Latvian Lowland in west cuts through the Baltic Morainic Ridge and separates the Latgale Upland from the Augšzeme Upland. The main geomorphological element within the Augšdaugava Depression is the terraced valley of the Daugava, where entrenched meandering of river flow is characterized by relatively high stream gradient as 0.16 m km^{-1}. The valley in this stretch is up to 45 m deep and from 0.5 to 1.2 km wide, gentle slopes along convex banks of accumulative terraces alternate here with very steep slopes along the undercut concave banks of the meander bands.

The local relief and geology of the case study area were largely formed by glacial processes during Pleistocene glaciations, particularly by the last Weichselian event (Zelès & Markots 2004). However, the valley of the Daugava river as geomorphological feature differs from the rest of landforms in this region due to it is a proglacial spillway initially formed by ice sheet meltwater streams during the Late Pleistocene and subsequently modified by fluvial processes in Holocene (Eberhards 1972, Āboltiņš 1994). Fluvial forms formed by gully erosion are characteristic features in this valley (Fig. 1B). There are more than 340 permanent gullies of different size and morphology dissecting the main valley sides along its 50 km long stretch from Kraslava down to Naujene, and total gully length per unit area in some places reaches 4.2 km km^{-2} (Soms 2006). Local altitudes range between c. 90 m a.s.l at the valley bottom and 150–170 m a.s.l at adjoining hummocky and undulated areas typical for uplands in Latvia. That also determines the considerable average difference in local topography, which is about 25 to 45 m, as well as high location of headwater catchments over the local base level.

The pre-Quaternary bedrocks of Devonian marine sedimentary rocks within the entire study are covered by thick cover of Quaternary sediments, thus spatial geological structure in the study area is characterized by lithostratigraphic sequence where stony sandy clayey diamicton and basal till deposits or glaciolacustrine clay and silt deposits of last glaciation origin were covered by younger Holocene gravely sand, sand and sandy loam alluvial deposits (Juškevičs et al. 2003).

The climate in SE Latvia is temperate semi-humid influenced by westerly winds, with moderate winters and warm summers. The mean annual precipitation usually varies from 600 to 700 mm yr^{-1}, distribution of precipitation over the year is rather even with no dry season. The mean temperature in January ranges from –7°C to –5°C; and in July from +16°C to +17°C. The recurrence of heavy rainfall events (more than 20 mm d^{-1}) which can cause hydrological extremes is 10 years or more.

Formation of runoff and values of discharge in gullies is determined mainly by the amount of snow accumulated in the headwater catchments during winter, rate of the increase of air temperature, intensity of snow melt in spring, and subsequent groundwater drainage. To a lesser extent it is determined by precipitation during warm period. Hence the seasonal distribution of precipitation and surface runoff are non-synchronous. The maximum discharge in gullies is usually observed in the end of March to April, during the intense snowmelt. It varies to a great extent in interval from 0.0001 to 0.1 $m^3 s^{-1}$ (temporary reaching values up to 0.17 $m^3 s^{-1}$) and depends on size of contributing area and other factors (Soms & Gruberts 2008).

Vegetation cover in territory under study is mainly represented by broad-leaved forests on stony and gravelly sandy loam luvisols, formed on glacial, glaciofluvial, and alluvial deposits.

Materials and methods

In order to get insight into gully erosion issues and to reconstruct the factors that led to development of different types of gullies in the case study area within the Daugava river valley, complex geomorphological studies of permanent gullies were performed by applying cartographic analysis, field research, GPS and GIS techniques.

For this purpose at first the analysis of topographic maps (coordinate system CK-42) at scale 1:10,000 and elevation contour interval of 2 m was done to locate all gully incisions within study area by applying the standard procedure of interpretation of fluvial landforms from maps (Easterbrook & Kovanen 1999). In total, more than 340 linear landforms with evidences of gully erosion in different geomorphological settings have been identified on the basis of the interpretation of topography. The draft lines of thalwegs and watersheds of gully catchments were derived from these topographic maps. Simultaneously, cartographic analysis was used to identify and to locate representative gully complexes of different morphological types for further field research. Considering the absence of LIDAR data for the study area, later the same topographic maps also

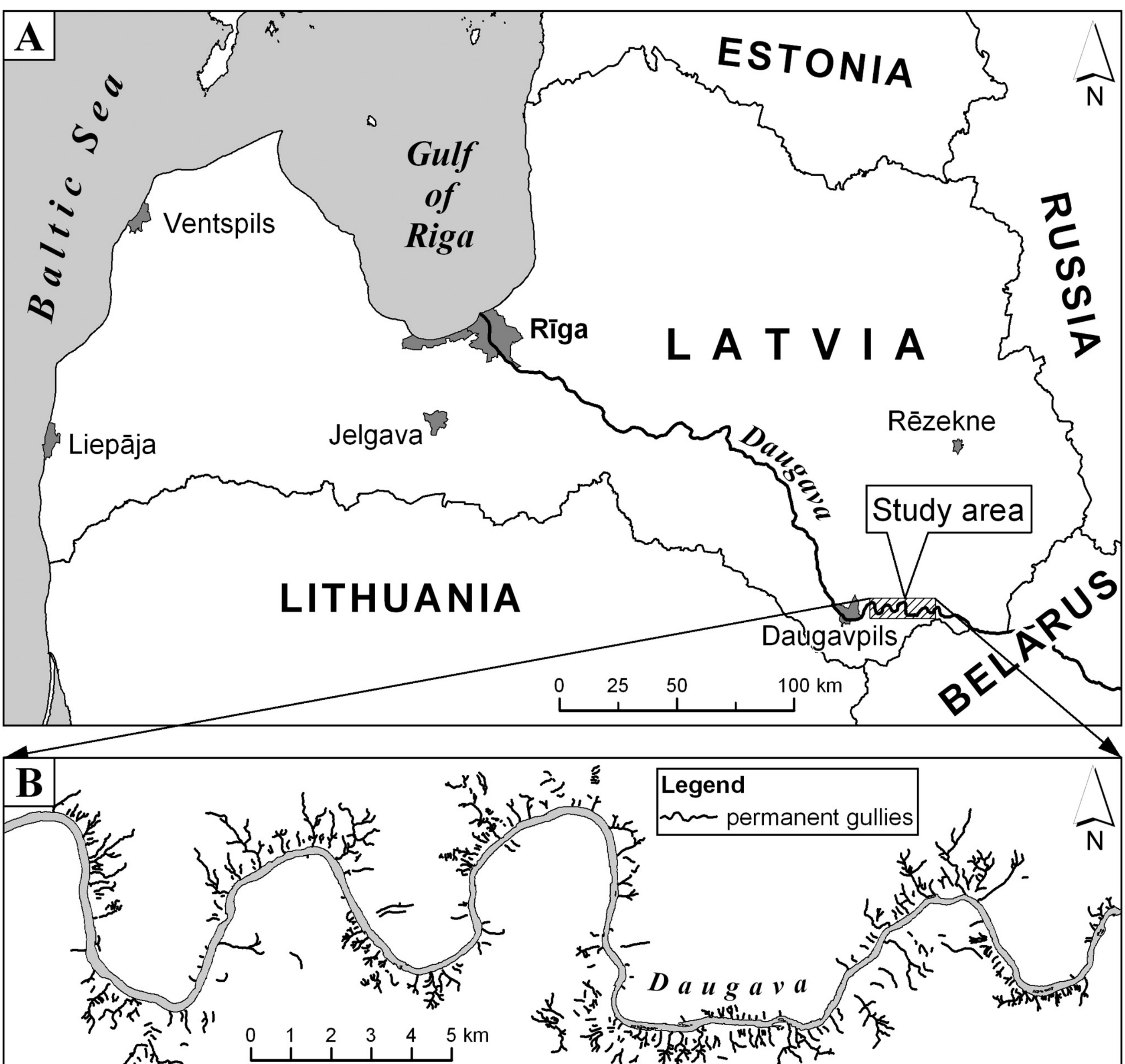

Fig. 1. Location of study area (A) and permanent gully network within it (B)

were used to construct digital elevation models (pixel size 2×2 m) by digitising and interpolating procedures.

After selecting and locating the gully catchments in the study area, precise delineation and mapping of selected representative gullies and their watersheds was carried out during field survey by GPS (THALES MobileMapper CE). Mainly because of a dense canopy of broad-leaved forests that are common in old gullies of this region, errors remained (a maximum error up to several meters) even after the differential correction. The obtained data were converted into *.shp format GIS files for further import and processing by ArcGIS software.

In order to obtain data on spatial distribution and proportion of vegetation cover within gully catchments, 1:10,000 aerial photographs flown 2005 were studied and used for digitizing. The area of both gully catchments, and vegetation-covered sites were calculated from the previously prepared geospatial data and digitized vector polygons using the ESRI GIS software ArcMap 9.3.1, and corrected by comparing with GPS data.

Thereafter field studies were applied for obtaining of relevant geological, morphological and topographical characteristics of gullies and their catchments *in situ*. During field studies the depth, width, length, channel gradient and sidewall slope gradient of the gullies were measured by standard geomorphological techniques (Goudie et al. 1998) and conventional survey methods. Surveying of longitudinal profiles of the gullies was done by Leica digital laser level Sprinter 100M and Thales high-precision GPS model GlobalMapper CE. Gully cross-profiles were generated by AutoCAD 2008 LT software from the data collected during measurement of gully sidewall gradients along the sampling line perpendicular to the thalweg. These measurements were performed by precise oil damped AngleLevel clinometer (error 0.5°) placed on the rod of 1 m length, hence reducing impact of microtopography (Young et al. 1974).

Estimation of thickness of colluvial sediments in gully channels and fans was carried out with classical hand drilling by AMS auger. Series of drillings consisting of 5 to 8 drills each were done across the colluvium-infilled bed of representative old gullies in 3 sites along the thalweg – the first series in a proximal part near gully head, the second in middle part and the third in distal part near gully outlet. Simultaneously, core sampler with plastic containers was used to get undisturbed sediment samples from contact between colluvial sediments and eroded Quaternary bedrocks for further pollen analysis. In this case buried stony basal till deposits or very coarse sediments consisting of gravel and pebbles with sand matrix typical for eroded gully beds in this region were assumed to be the substrata. Pollen analysis was performed in the Quaternary Environment laboratory at University of Latvia by standard methods, in accordance with the procedures of Moore et al. (1991). Results of pollen analysis have been used only for interpretative purposes, e.g. presence of cereal pollens as indicator of human agricultural activities, not for absolute dating. Due to the lack of charcoal, organic matter or terrestrial vegetation macrofossils in drill-cores from contact between old gully bed and colluvium cover, only some radiocarbon dates were obtained by decay-counting dating of wood fragments. The dating was carried out in the Erlangen AMS Radiocarbon Laboratory of the University Erlangen-Nürnberg. The dates were reported as conventional radiocarbon dates corrected to a $\delta^{13}C$ of 25‰, and were calibrated using the Calib 5.0 calibration programme (Stuiver & Reimer 1993).

Dendrochronological techniques first described by Alestalo (1971) and further developed in last decades for assessment of gully erosion rates (Vandekerckhove et al. 2001) were used in this study to determine the time interval since erosion stabilization in landslide-gully complexes presently found under forest, where evidences of recent erosion were observed. For these purposes core samples from the stem of trees growing within the gullies were taken by means of an SUUNTO increment borer.

Finally geoarchaeological data given in literature (Berga 2007) were studied to determine the relationship between the gully formation process and appearance of settlements of prehistoric time in the case study area.

Results and discussion

In general, considering the formative processes and morphological differences, five main morphogenetic types of permanent gullies can be distinguished in the case study area: (1) flat-bottomed gullies (2) valley-bottom gullies or 'gullies-in-old-gullies', (3) hanging gullies, (4) valley sidewall gullies and (5) landslide cirque gullies. First four types of gullies according to Leopold & Miller (1956) can be classified as continuous, the last one as discontinuous gullies. The diversity and different morphology of gullies give rise to doubt about the same time of formation of these landforms and the simultaneousness of development of erosion network.

Flat-bottomed gullies

This type of gullies is represented by the largest fluvial erosion landforms among those draining zero-order catchments adjacent to the Daugava valley. These geomorphological features which have local name *vecgravas* are somewhat alike small dry grassed valleys and equals to East European *balkas*. Considering classification based on size (Frevert et al.

1955), these fluvial erosion landforms are large gullies. These flat-bottomed old gullies are characterised by impressive morphology, i.e. up to 15 m deep, up to 80 m wide, up to 2.0 km and longer with the typical trapezoidal cross-sectional profile (Fig. 2A).

Upper reaches of them crosses the edge of the valley and extend far into adjacent areas, i.e. more than 50% of their length are allocated within morainic plain and often are connected with local small glaciodepressions. Channel gradients in such gullies are gentle and vary from 0.012 to 0.028 m m^{-1} and longitudinal profiles of gullies have the concave equilibrium profile form. In upper reaches they have no imposing headcut due to long-term development of mass-movement processes and smoothing of the edges. There is no evidence of present erosion in gully bed or sidewalls due to dense turf cover, furthermore many of them partially or totally are covered by forest or shrubs. However, a lot of old, vegetation-stabilized hollows resulting from formation of landslides and short slope gullies can be identified on the sidewalls. Mean gully sidewall angles measured in flat-bottomed gullies varies from 12° to 18°, the maximum observed values reaches 36–38°, which is higher than repose angle for loam and sandy loam. It can be explained by presence of vegetation, which armour slopes by root system thus preventing the further lowering. The colluvium deposits have an average thickness of 2.1 m in upper reaches of flat-bottomed gullies and more than 3.5 m in lower reaches.

Generally in studies focused on old gullies, accurate input data for estimation of palaeoenvironmental conditions and hydrological parameters often are lacking. However, the Leopold & Maddock (1953) width-discharge relationship, extended on

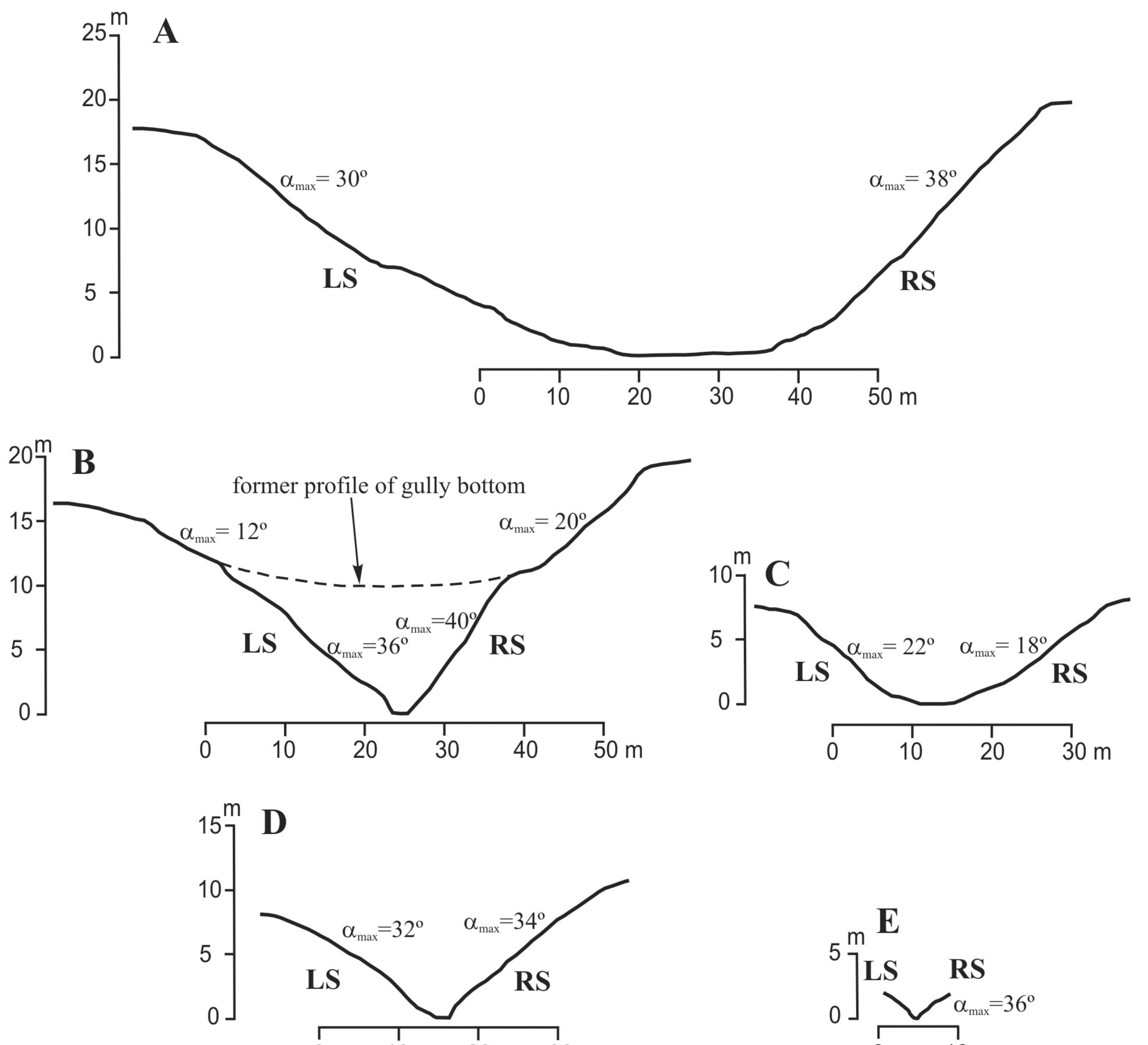

Fig. 2. Cross-profiles of typical gullies of different morphogenetic types in the River Daugava Valley: flat-bottomed gully (A), dell-bottom gully (B), hanging gully (C), valley sidewall gully (D) and landslide cirque gully (E); LS = left sidewall of gully; RS = right sidewall of gully; α_{max} = maximal slope gradient of measured cross-profile

rills and gullies (1) (Nachtergaele et al. 2002b, Torri et al. 2006) could be applied for old gullies (Vanwalleghem et al. 2005b) in order to get the approximation of the peak flow discharges (Q) that had to caused incision of given width (*W*), i.e.:

$$W = 2.51\ Q^{\ 0.412} \qquad (1)$$

from which one gets:

$$Q = 0.1072\ W^{\ 2.427} \qquad (2)$$

Considering that flat bottom of such gullies are formed by subsequent aggradation due to a combination of mass movement and fluvial deposition processes, field measurements of *W* of an old gully will probably never be equal to the original size of that at the time of gully formation. However, geological field survey of old gullies performed by author and the data reported in the literature (Vanwalleghem et al. 2005b) allow assessing effect of the evolution of the gully cross-sectional area through time on measured gully bottom width. Basically aggradation of gully channel results in an underestimation of *W* values and as a consequence, *Q* values will be underestimated.

Despite the criticisms about the reliability of results obtained by using of this method, it is still widely used because of its simplicity and necessity of only a few input parameters. Using equation (2) and the values of measured width as 16 to 20 m at the bottom of the studied old flat-bottomed gullies within the case study area reveal that *Q* should be about 150 $m^3 s^{-1}$ and more. It follows that formation of such concentrated discharge is virtually impossible at persisting vegetation cover and Holocene climate conditions in south-eastern part of Latvia.

It let us to assume that formation of flat-bottomed gullies was initiated in periglacial conditions by intensive streams resulting from melting stagnant glacial ice blocks during the retreat of ice sheet from SE part of Latvia (Zelčs & Markots 2004), at the end of the Late Weischelian glaciation, Late Pleistocene, about 14–12 ka BP (Lundqvist & Saarnisto 1995). It also corresponds with data given by other scientists (Langohr & Sanders 1985, Panin et al. 2009) who suggested that such old gullies could be periglacial geomorphic features. The dating of wood buried under colluvium in this gullies reveal age 1990±75 BP, ca. 190 cal BC – 170 cal AD (Erl-10456), which does not tie in with previous assumption. However, ^{14}C dates actually indicate the time when last period of infilling began, but do not the time has passed since gully initial formation. Considering the methodological difficulties of dating such gullies (e.g. redeposition of organic matter – Panin et al. 2009), as well lack of material suitable for decay-counting dating buried under colluvium, in the future it is necessary to obtain OSL dates. Considering the mean sediment thickness within flat-bottomed gullies and ^{14}C dating of age of wood buried under these sediments, the mean annual rate of colluvium deposition during the last period of infilling was calculated. Obtained results, i.e. 0.0011 m yr^{-1} coincide with data about accumulation rates in gullies located in similar physiogeographic environment (Smolska 2007).

Dell-bottom gullies

The dell-bottom gullies or 'gully-in-old-gully' erosion landforms are large gullies of complex origin, composed from the gentle U-shaped older landforms and incised into them younger V-shaped gullies. Considering their topography gullies of this type correspond to the valley-bottom gullies of Bradford and Piest (1980). These gullies together with ones of previous type are the main drainage elements which drain the rolling morainic landscape adjacent to the valley and play an important role as effective links for transferring runoff resulting from precipitation and snow melting to the river.

The dell-bottom gullies have lengths of over 0.5 km; some of them stretch up to 2.3 km, and depths of over 15–20 m. Like flat-bottomed gullies, these erosion landforms deeply dissect the slopes of ancient glacial spillway and their headcuts extend far into headwater catchments, while their outlets or fans were approaching the sub-horizontal surface of terraces or floodplains, or protrude directly into the Daugava river channel. Characteristic feature of these gullies are the dendritic branching in the middle and upper stretches due to development of branch gullies on the headwater catchment. Formation of such branch gullies occurred mainly in deeply incised gullies, where gully thalweg cuts through permeable Quaternary sediments and reaches groundwater table, eventually triggering lateral seepage erosion in the gully sidewalls. Applying the system of stream ordering (Strahler 1952) to gully erosion landforms, such gullies can be accentuated as second-order or third-order gullies.

Mean gully sidewall angles measured in the upper part of cross section of dell-bottom gullies differ from ones measured in the lower part, i.e. 12° to 18° and 20° to more than 35° respectively. There are not colluvium deposits within channels of such gullies, and instead of infilling, the evidences of recent erosion were observed. The complex, terraced-like cross sections of these gullies (Fig. 2B) show an evidence of more than one incision event forming younger gullies in the bottom of older ones or dells as a response to the formation of concentrated runoff resulting from climate and human impact.

Formation of gullies of this type can be associated with reactivation of erosion processes within the flat-bottomed gullies due to climate factors (excessive inflow of water resulting from extremely heavy rainfalls) or anthropogenic factors (redirecting of artificial drainage system, i.e. melioration ditches and subsurface pipe outlets into upper reaches of gullies). Thus dell-bottom gullies developed by leaps over a long time period and reveal consequences of different formative processes. It is very possible that they have the same age as the flat-bottomed gullies. Indirectly such assumption is ascertained by geoarchaeological data obtained about the history of ancient settlements in the case study area. According to Berga (2007), the first culture of Balts characterised by farming lifestyle and use of slash-and-burn agriculture settled in this area in the Middle Iron Age, ca. 5th and 9th century AD. Cultivation of land and, therefore, forest clearance could trigger the reactivation of gully erosion. However, this culture as settlement places chose 'naturally fortificated' sites where valley slopes already were dissected by deep gullies, it follows that these gullies were formed before the human agricultural impact.

Hanging gullies

This distinctive type of old gullies has rather rare occurrence in the Daugava valley. Hanging gullies actually are transformed to flat-bottomed gullies, which initially were approaching the local base level and after the stabilization and reducing of sidewalls gradients had the same morphology as balkas. However, during the subsequent development of meanders and widening of the valley by lateral erosion, the river eroded and washed out terraces, alluvial fans and lower reaches of flat-bottomed gullies. During repeated regional incision period of the river, a younger terrace was formed at a lower level, but partially cut old gullies were left as the hanging gullies, whose flat bottom lies now 12 to 14 m above the present local base level. The present thalwegs of hanging gullies intersect plane of slope in the middle or lower part of the valley sidewall and does not reach the local base level, leaving outlet of gully in hanging position. The erosion process is not renewed in these hanging gullies because of a turf cover on bottom and slopes that prevent downcutting. Hanging gullies have gentle U-shaped cross-profiles (Fig. 2 C), however, in comparison to other types of old gullies these landforms characterize smaller dimensions, i.e. lengths of over 0.2 km to 0.3 km and depths of 8–12 m.

Estimation of the river terrace development periods (Eberhards 2000) permits us to conclude that hanging gullies can be defined as 7,000 to 9,000 BP (^{14}C dates Ri-320 and Ri-323). It means that these gullies were formed in the pre-agricultural times, towards the end of Boreal or at the beginning of Atlantic period. Pollen analyses of samples obtained from these gullies unfortunately do not provide information on the time of formation. Quantitative and qualitative differences of pollen grains content in samples indicate sediment redeposition within gullies thus making pollen diagrams unreliable.

Valley sidewall gullies

Morphology of gullies of this type is very similar to the bank gullies of Poesen et al. (1996), and resembles the continuous gullies of Leopold & Miller (1956). These landforms have been characterised by high values of topographic parameters, however, usually they are smaller in comparison to flat-bottomed gullies and valley-bottom gullies. Lower reaches of them dissect the valley sidewalls, while upper reaches of them crosses the edge of the valley and extend far into adjacent areas. In terms of the gully length, more than 50% of their stretches are allocated upslope from the edge of the valley within morainic plain. Like the dell-bottom gullies, the valley sidewall gullies extensively branch upslope and forms dendritic pattern of erosion network. Typically depth of these gullies range from 5 to 10 m and more, and cross-profiles are V-shaped (Fig. 2 D). The observed values of the slope gradient reach 36° and more, which is higher than repose angle. It can be explained by continuation of erosion and mass movement processes within these gullies. Formation of these gullies, like the reactivation of erosion in the dell-bottom gullies, were triggered by localized high-intensity rainstorms in agricultural landscapes or by inappropriately established melioration system, when drainage ditches or outlets were allocated along the edge of the valley.

This type of gullies differs from bank gullies reported in studies of European loess belt. The differences are mainly determined by morphological peculiarities of gully channels. Gully incisions of this morphogenetic type do not correspond to equilibrium longitudinal profile. During the downcutting process, fine to medium grained sand and silt particles were washed out from the channel floor leaving litter pebbles and boulders. As a result of the continuous aggregation of pebbles and boulders washed out from stony basal till boulder-floored gullies have been formed. In its turn the occurrence of such erosion resistant debris in the lowest part of gully facilitates convex or step-like longitudinal profiles with knick points. Such convex knick points indicate that at the boulder-floored stretches of gullies the further downcutting is impossible.

Landslide cirque gullies

This type of gullies is represented by short discontinuous gullies developed on the steep slopes along undercut concave banks of the meander bands. Similar landforms regarding their morphology and formative processes, i.e. gullying is induced by mass movements, have bend examined by Parkner et al. (2007), who use term "slide complex". Landslide cirque gullies typically have bottleneck shape with cirque-like or amphitheatre-shaped sub-circular depression at the gully head and shallow, V-shaped cross-profile at the gully outlet (Fig. 2E). A large number of small springs (discharge less $0.05\ \mathrm{l\ s^{-1}}$) and sapping signs, which can be observed at the bottom of landslides scarp, usually form small streams. This indicates that these landslide–gully complexes were initiated by seepage erosion.

Landslide cirque gullies are short (15 to 90 m), the depths of the incisions vary from 0.8 to 2.5 m and gully catchments are relatively small, from 0.29 ha to 1.22 ha. Taking into account volume of eroded sediment, they can be compared with ephemeral gullies. However, from ephemeral gullies they differ by step-like thalweg and steep longitudinal profile (channel gradient $>0.4\ \mathrm{m\ m^{-1}}$). Using of equation (2) let us to calculate discharge of spring outlets, which possibly forms these gullies. Calculation shows, that discharge have to be from $0.0058\ \mathrm{m^3\ s^{-1}}$ ($W = 0.3$ m) to $0.0831\ \mathrm{m^3\ s^{-1}}$ ($W = 0.9$ m). Comparison of data shows that theoretically calculated values is almost 2 orders as large as those obtained by measurement of real spring discharges in-situ.

This fact can be explained by assumption that gullies are not formed entirely by focussed groundwater seepage and spring outflow, but also by landsliding processes and surface runoff concentrated in landslide cirques. On the other hand, steep channel gradient obviously plays an additional role in accelerated erosion. Steep longitudinal profiles create favourable conditions for formation of micro-waterfalls due to collapse of colluvium in gully channel, which in turn invokes a variety of small scarp failures that intensify backward erosion.

Applying of dendrochronological techniques reveals that these gullies are rather new. Trees, growing in these gullies are 72–76 years old. Considering the observations (Parkner et al. 2007) that vegetation rapidly re-colonized the scours and the slopes of recent landslide cirque gullies, it is possible to assume that gullies were formed shortly before trees took roots. Hence the formation of these gullies are related to the intensive undercutting of the Daugava valley bluffs during very extreme spring floods (probability of occurrence 1 to 0.5%) in 1931.

Conclusions

Although many studies have linked the triggering of gullying processes to changes in landscape and land cover resulting from human agricultural activity, it is most likely that the origin of gullies in the Daugava river valley, particularly those presently found under forest, is more complex than that and the gullies are temporally polygenetic geomorphological features. Such assumption corresponds to an opinion shared by other scientists that erosion events and formation of gullies could took place before the anthropogenic impact became a significant factor or even in areas with undisturbed canopy vegetation. In some sense these old gullies could be compared with pages of palimpsest. i.e. medieval manuscript where text has been erased off and written over again, hence gullies in the study area geomorphologically reflect several incision–accumulation cycles of the erosion network development.

Depending on empirically estimated mean annual rates of colluvium deposition, ^{14}C dates and pollen analysis, we can conclude that old gullies of the study area formed before the beginning of intensive agricultural activities in the Daugava river valley and that the infilling of them belongs to Subatlantic time ca 2000 yr ago.

Important factor of reactivation of erosion process in old gullies and formation of new valley sidewall gullies in the Daugava valley was melioration measures, when surface and subsurface runoff by means of drainage ditches or melioration pipes was concentrated and redirected into old gullies or downslope elongated linear depressions.

Estimation of time of development of landslide and erosion complex – landslide cirque gullies – demonstrate, that their formation is related to undercut of the valley bluff during devastating floods in the river Daugava in the thirties of the 20th century.

Acknowledgements

Research reported in this paper was financially supported by the ESF project No. 2009/0138/1DP/1.1.2.1.2/09/IPIA/VIAA/004 "Support of doctor's studies in University of Latvia". The author is grateful to E. Iliško, D. Kursits and M. Petrovs for their assistance in the fieldwork.

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