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Regularities of gully erosion network development and spatial distribution in south-eastern Latvia

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Abstract Initial development and further spatial distribution of the gully erosion network depends on many factors and varies in regions with varying landscape, climate and land-use. However, in Latvia these factors are the topographic and geological indicators that have mainly determined the spatial distribution and morphological features of gullies. In this paper, gully erosion network and gullies in upland areas within south-eastern part of Latvia is studied in relation to the geological and geomorphological structure of the territory. Interpretation of gully patterns, GIS analysis of the erosion network density and field studies of gully morphology have been carried out. Comparison of the obtained data with data of geological mapping show direct correlation of the erosion network distribution with the topography and geological structure in the study area.

Keywords *Topographic and geological indicators, gully erosion network, spatial distribution.*

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INTRODUCTION

Gully erosion is a widespread geological process of denudation, fluvial network development and landscape evolution caused by diversification of relief. At the same time development of gullies is associated with the accelerated soil erosion on cultivated plots and degradation of agricultural land, hence gully erosion has been recognised in many countries as an environmental problem (Valentin *et al.* 2005). A reference review reveals that this problem has been studied from the different points of view in Western Europe (e.g. Nachtergaele *et al.* 2002; Poesen *et al.* 2003; Valentin *et al.* 2005; Vanwalleghem *et al.* 2005), however most of studies hitherto focus on gully development under cropland.

A lot of gullies as fluvial landforms can be also found in Latvia, but only some studies have reported factors controlling their genesis and regularities of spatial distribution (Stalbovs 1977; Soms 1999). In its turn, the lack of available scientific data does not allow to evaluate the impact of global environmental change and variability of meteorological factors on concentrated erosion by water in Latvia, though assessing the expected consequences of geomorphic processes and hazards due to climatic changes is the objective of national and international researches (e.g. Favis-Mortlock, Boardman 1995; Poesen *et al.* 1996; Collison *et al.* 2000; Dehn *et al.* 2000; Nearing 2001; Poesen *et al.* 2003; Sidle *et al.* 2004). Projected models of Europe's changing climate show a 1to 2% increase per decade in annual precipitation (Impacts of Europe's changing climate 2004) and a 10 to 50% increase in the annual river discharge by 2070 (Lehner *et al.* 2001) in the northern and north-eastern Europe. Such changes of climate factors and hydrological regime will relate to all elements of fluvial systems from small catchments to regional river basins, therefore these changes will trigger increase of runoff and intensification of accelerated erosion by water in existing gullies.

This demonstrates the need for monitoring, experimental and modelling studies of gully erosion as a basis for predicting the effects of climatic changes on the rates of gully erosion, as well as for the evaluation of possible renewing of incision processes in inactive gullies in Latvia too.

In order to interpret the thresholds and geological and topographic factors controlling the development of gullies presently found in SE Latvia, as well as to elucidate regularities of spatial distribution in gully erosion network, permanent gullies in the Latgale Upland, Augšzeme Upland and River Daugava Valley are studied. The specific objectives of this study are (1) to obtain data *in situ* on morphological and topographical characteristics of gullies in the environments with a differing topography; (2) to determine patterns of the gully network and to calculate the gully network density; (3) to correlate the obtained data with geology and topography of the study area.

STUDY AREA

The investigation of gully erosion network is performed in the case-study area of the Latgale Upland, Augšzeme Upland and River Daugava Valley indicated in Fig. 1. The territory of south-eastern glacial uplands encompasses 8423.3 km^2 of the entire Latvian territory and could be subdivided into three large scale landforms, which differ by genesis: the Latgale Upland (an insular shaped and bedrock cored glacial upland by Āboltiņš 1989; Āboltiņš 1995) covers 79%, the Augšzeme Upland (a marginal glacial upland by Āboltiņš 1994b) – 19%, and the River Daugava Valley (a proglacial spillway valley modified by fluvial processes by Eberhards 1972; Āboltiņš 1994a) – 2% respectively.

The present day topography and geology of this territory has been largely formed by Pleistocene glaciations, particularly by the last Weichselian (Vistulian) event (Zelčs, Markots 2004). The highest point of the Latgale Upland is Lielais Liepukalns (289 m a.s.l.) and of the Augšzeme Upland – Egļukalns (220 m a.s.l.). The average difference in local topography is about 10 to 25 m with its maximum up to 50 to 60 m in glacial uplands and in some places along subglacial tunnel valleys. The mean height is 175 m a.s.l., however, almost 97.8% of study territory situated below 200 m a.s.l., and elevations over 250 m a.s.l. occupy only 0.03% of the area. The territory is characterised by a temperate semi-humid climate influenced by the westerly winds. The mean annual precipitation varies mostly within 600 to 700 mm/yr; number of days with precipitation 100 to 120 d/yr; mean temperature in January from –7°C to –5°C; the mean temperature in July from +16°C to +17°C; recurrence interval of extreme rainfall events (more than 20 mm/d) is 10 years and more.

Soils occurred relatively quickly in Latvia because the glaciation that ended about 10000 years ago had deposited an abundance of easily weathered ground-up parent material. Soils formed mainly on glacial, glacifluvial and alluvial deposits. They also pose environmental problems, for they are easily eroded into rills or even gullies by relatively small streams, at the same time they are susceptible to mass movement like solifluction and earth-flows. Hence the geological structure (erodible glacial, glacifluvial and glaciolacustrine Quaternary top layer deposits), geomorphological indicators (form, gradient and length of slopes) and climatic factors (quantity and intensity of precipitation, intensity of snow melting, winter conditions) create favourable environment for accelerated soil erosion within the study area.

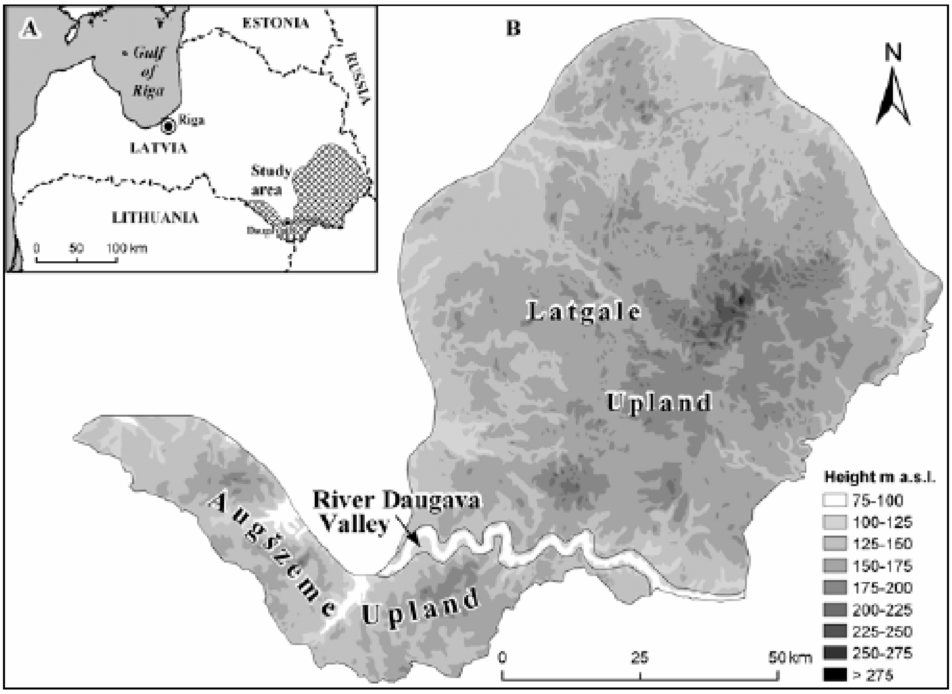

Fig. 1. Location (A) and digital elevation model (B) of the study area.

MATERIAL AND METHODS

Analysis of topographic maps

The analysis of topographic maps was carried out to locate all representative channel-like incisions in the study area. The lines of thalwegs and watersheds, and areas of gully catchments were derived from topographic maps (coordinate system 1963) in scale 1:10,000 and elevation contour interval of 2 m. Later these maps were used to construct digital elevation models (DEM) (pixel size 2x2 m) by digitising and interpolating procedures.

Field studies

During field studies the depth, width, length, channel gradient and sidewall slope gradient were measured by standard geomorphological methods (Blong 1972; Gardiner, Dackombe 1977; Goudie *et al.* 1990). Morphology of smaller gullies (width less than 30 m, depth less than 15 m) was measured by two T–coupled fibreglass measuring tapes (length 50 m, accuracy ±5cm/50m). When the gully width exceeded 30 m, it was measured by Bushnell Yardage Pro 500 laser rangefinder (accuracy ±10cm/100m). Width and depth were measured several times along each gully in order to determine maximum values. Sidewall slope gradients were determined with a clinometer (type Suunto, error 0.005 m/m). At the same time morphology of gully channels, forms of cross-profiles and longitudinal profiles, as well as the type and intensity of geological processes in gullies were assessed. An AMS auger hand drill kit was used to collect data on filled cross-sections of permanent gullies.

Geomatic studies (GPS and GIS)

After analysing of topographic maps and locating linear erosion landforms in the study area, representative gullies were identified during field studies and their position was mapped with GPS (Trimble GeoXT). Mainly because of a dense canopy of broad-leaved forests that are common in gullies, errors remained (a maximum error up to several metres) even after the differential correction. The obtained data were converted into *.shp format GIS files for further importing and processing by GIS software. The lines of gully thalwegs and watersheds, and the areas of gully catchments were digitised from topographical maps (scale 1:10 000) using the ESRI GIS software ArcMap 9.0, and corrected by comparing with GPS data. 2 m contour DEMs (pixel size 2x2 m) of the selected areas were developed by digitising and interpolating the topographical maps (scale 1:10,000) using the ESRI GIS software ArcMap 9.0 and extension SpatialAnalyst 9.0. The spatial analysis and calculating of gully network density was made by GIS. Finally, principal geomorphological, geological, climatic and anthropogenic factors which have affected gully erosion were studied to determine the correlation between the intensity of gullying and the factors mentioned above.

RESULTS

Field studies, analysis of topographic maps and spatial analysis of the arrangement and spatial distribution of gully network show that erosion landforms are rather common in upland areas of SE Latvia where gullies formed predominantly on the slopes of river valleys and subglacial tunnel valleys, as well as on the slopes of morainic hills and plateau-like hills. Whereas in lowland areas of SE Latvia gullies occur occasionally and are not common feature in general. The distribution of gully erosion landforms is mainly determined by the location of glacial and fluvial landforms. This fact could be illustrated by the regularities studied in the selected model territories.

Development and location regularities of gullies in river valleys

Conclusions about the development and location regularities of gullies in the model territory of the River Daugava Valley from the town of Krāslava down to the Naujene Village are based on the field data. Within this 48 kilometres course of the river the total number of gullies is 352 registered and measured.

Non-branched, from 100 m to 400 m long permanent gullies of the 1st or 2nd order, which are crossing the edge of the valley are a predominant type in this area. The expansion range of gullies of a higher (2nd to 4th) order is much lower. Gullies of the 5th order have not been registered in the study area. Gullies in the model territory range from 2 to over 20 meters in depth and from 8 to over 100 meters in width. The largest of them are flat-bottom dry valleys indicated in Fig. 2, and are characterised by impressive morphology (up to 15 m deep, up to 80 m wide, up to 1.5 km and more long).

Short ephemeral gullies incised into the valley slopes and terraces, as well as hanging gullies are also widespread. Hanging gullies started to develop as ordinary gullies when their temporary base level of erosion was equal to the river floodplain surface. The growth and incision of such gullies stopped when they had cut their thalweg closer to the base level, their longitudinal profiles reached the concave-upward equilibrium longitudinal profile form, and their lower ends were approaching the local base level. In that situation the steepness of walls was reduced by mass movement processes (e.g. slumps, landslides etc.), gully thalwegs were filled with silty sediment washed down from the

Fig. 2. An inactive gully, located within the River Daugava Spillway Valley near Slutiski, 21 km east of Daugavpils.

slopes, and vegetation slowly covered gentle slopes of former gullies. Eventually gullies transformed into inactive small flat-bottom dry valleys or *balka**.

Changes in the regional base level of the River Daugava, its lowering (Eberhards 1977) and the renewal of down-cutting process transformed the former floodplain into a valley terrace. Stabilisation of a regional base level after a short but intensive down-cutting period caused the reduction of a gradient, deposition of sediment in the stream channel and the process of meandering. During the development of meanders and widening of the valley by lateral erosion, the river eroded and washed out terraces, alluvial fans and lower parts of former gullies or *balkas*. During the following valley down-cutting period, the river formed a younger terrace at a lower level, but partially cut former gullies were left as the hanging gullies, whose flat bottom lies now 12 to 14 m above the present local base level of erosion. The down-cutting process is not renewed in these hanging gullies because of a turf cover on slopes and vegetation that prevent erosion processes. Estimation of the river terrace development periods (Eberhards 1977) permits us to conclude that hanging gullies can be defined as 9000 to 11000 cal. BP. It means that these gullies were formed in the pre-agricultural times, towards the end of Younger Dryas or at the beginning of Holocene.

The longest and deepest gullies have developed by leaps during several short reactivation periods together with the Daugava River Valley formation process and according to the changes in a regional base level of the river and formation processes of the terraces. The complicated cross and longitudinal profiles of gullies testify to this fact. Ephemeral gullies in landslide cirques and short ephemeral gullies incised into slopes of valleys and terraces are comparatively young, in its turn hanging gullies and flat-bottom dry valleys are older.

Human activities, e.g. directing drainage water flow into gullies, forest cutting, turf cover destroying, soil cultivating etc., as well as heavy rainfalls have stimulated the renewal of erosion processes in inactive gullies and even in ancient gullies or *balkas*. Fresh V-shaped down cuts in the bottoms of gullies and alluvial fans demonstrate that. However, the formation of new deep gullies in the model territory has not been observed during the last 50 years.

The exposure of slopes (aspect) of the Daugava River Valley is a second-grade factor, which has affected the development and location of gullies. The data correlation between the gully network density and the exposure of slopes in this area shows that the gully network density on the slopes of southern exposure is only 5 to 8% higher than that on the slopes of northern exposure.

Maximal values of the number of gullies along the river bank (up to 14 gullies per 1 km of a river bank) and the highest density of the gully network have been registered on the territories where the erosion base level exceeds 30 m, the slope inclination is more than 15°, slopes have a convex form, their length exceeds 100 m. These slopes are composed of stony sandy clayey diamicton and basal till deposits. The complex of factors mentioned above has been registered mainly along the undercut concave banks of the meander bands (Fig. 3). The most complicated landscape and the most intricate topography of slopes relate exactly to such sections of the river valley, where the highest density of gully network (up to 4.5 km/km^2) in the territory under consideration has been ascertained. The most commonly encountered gully network pattern is of dendritic character.

The rate of gully erosion dramatically accelerates in places where the slopes of the river valley are built up by erosion resistant clayey or silty till overlying a glacifluvial fine to medium grained sand layers. In these localities also mass movement processes mainly formation of landslides and slumps are common. These geological and exodynamic factors lead to the formation of the morphologically specific gullies in landslide cirques as a result of piping.

The greatest part of the measured thalwegs of gullies do not correspond to the concave equilibrium longitudinal profile. During the down-cutting 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 concentration 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 portions of gullies the down-cutting is impossible.

* Balka – geomorphological term used in Russia to describe gullies transformed into inactive flat–bottom dry valleys (Dokuchayev 1877).

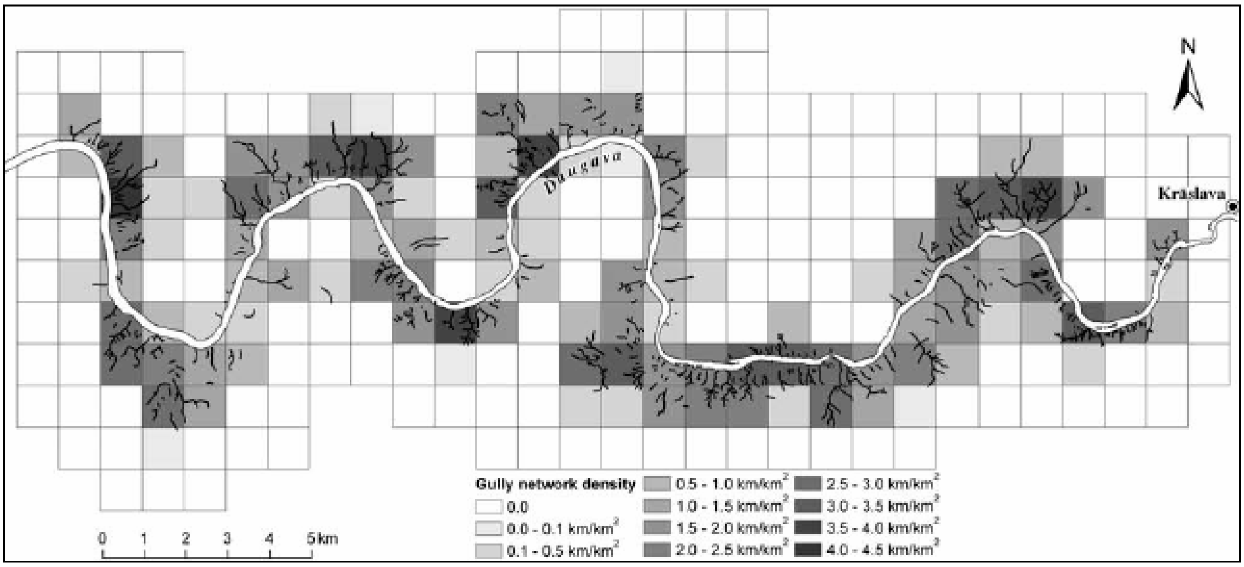

Fig. 3. Spatial distribution of gullies in the River Daugava Valley from Krāslava down to the Naujene Village and computed gully erosion network density.

Development and location regularities of gullies in areas of plateau-like hills

The density of gully network up to 1.2 km/km^2 has been registered in the northern part of the Latgale Upland. The plateau-like hills or zvoncy are the most common feature of glacial landscape of this area. The relative height of plateau-like hills exceeds 15, with a maximum up to 35 to 40 m. These hills have relatively steep slopes (gradient up to 20° to 40°) which in places are terraced (Meirons 1975). The base of these hills is made up of glaciotectonically deformed till strata encompassing the glacioaquatic deposits (Āboltiņš 1989). Tops of the plateau like hills have a flat surface. Besides the topmost part is formed from glaciolacustrine clay. As a result of the morphological features and complex geological structure favour to a great extent the formation of the gullies on the slopes.

The data obtained during field studies and map analysis in the model territory show that long and deeply incised gullies dominate on the slopes of the plateau-like hills which flat-topped area covers about 1 km^2 and more. If the area of the plateau-like hill top surface is lesser only short ephemeral gullies occur.

Due to the flat hilltops of glaciolacustrine clay and steep slopes of till infiltration rate is too low to absorb falling rain or melting snow. It causes the runoff concentration into small streams and rill erosion. If these rills are not destroyed, they soon begin to integrate and form gullies. The rugged topography of plateau-like hill slopes indicated in Fig. 4 is formed by the 100 to 400 m long 1st order, and in some places by the 2nd order permanent gullies. The exposure of plateau-like hills slopes, like in the previously described model territory, is of little importance on the development and location of gullies. Gully network spatial distribution can be described as the radial pattern.

The principal geomorphological factors that have affected gully erosion are the following, temporary erosion base level (relative height of a plateau-like hill), inclination and length of slopes. Formation of gully network has been registered on the plateau-like hill slopes, the length of which exceeds 50 m, the slope gradient is at least 8° to 10° and the erosion base level exceeds 20 m.

The flat surface of plateau-like hill tops and fertile soils, which were formed on a glaciolacustrine clay subsoil deposits, caused favourable pre-conditions for agriculture and attracted ancient farmers. Taking into consideration the fact mentioned above, it could be concluded that in this model territory the formation of gullies is related to intensive forest clearing as result of slash-and-burn agriculture and beginning of soil cultivation in the 9th and 10th centuries (Strods 1992). To verify this assumption, it is necessary to obtain radiocarbon or/and OSL dates.

Development and location regularities of gullies on the slopes of subglacial tunnel valleys

Glacifluvial landforms and tunnel valleys are particularly widespread in the Augšzeme and Latgale uplands (Eberhards 1977). The relative depth of such forms varies from 20 to 35 m. The depth and the steep slopes (20°to 40°) of the tunnel valleys are the most common geomorphological conditions for gully formation in these areas.

The density of gully network up to 0.6 km/km^2 has been registered in model territories of the Latgale and Augšzeme uplands. The rugged topography of the tunnel valleys slopes is formed by short 80 to 150 m long non–branched permanent gullies of the 1st order. The expansion range of the 2nd order gullies is much lower. Gully network spatial distribution can be described as the subparallel pattern.

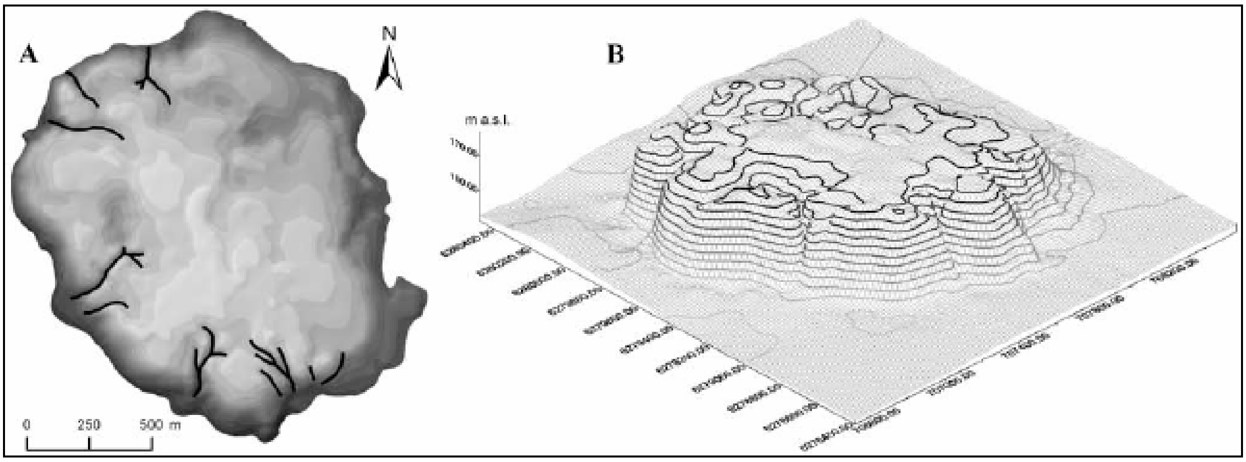

Fig. 4. DEM (A) and 3D model (B) of plateau-like hill 8 km north of the town of Rēzekne depicts spatial distribution of gullies and radial pattern of erosion network.

The correlation of the data obtained during field studies and analysis of data derived from topographic maps show that the degree of the gully erosion is mainly determined by the slope gradient and temporary erosion base level, in fact by the depth of tunnel valleys. Low values of the erosion base level (10 to 15 m) and gentle slopes (less then 10°) have determined the inactivation of linear erosion after the formation of rills. Deeply incised permanent gullies have been formed predominantly on the slopes of those tunnel valleys, which depth exceeds 25 m, and the angle of slope inclination exceeds 20°. The increase of the stream erosion potential was caused by the growth of its velocity and the height of the erosion base level. Short ephemeral gullies incised into the slopes of subglacial channels are also comparatively widespread.

It should also be emphasized that the internal structure of glacial deposits forming the slopes of tunnel valleys and neighbouring areas determines favourable conditions for the gully formation on the slopes of these landforms. As a rule, along the tunnel valleys the uppermost part of Quaternary sequence is made up by facies of massive basal till or silty diamicton (Āboltiņš 1989) that could be characterised of low infiltration indices. Consequently mentioned factor causes the concentration precipitation and snow melting water surface runoff and gully erosion.

Summing up it could be concluded that the development and location of gullies on the slopes of subglacial channels in SE Latvia are determined by the peculiarities of the geomorphological features, particularly surface topography and morphometry of slopes, and geological structure of Pleistocene glacial deposits.

DISCUSSION AND CONCLUSIONS

Many scientists (Haigh 1980; Besler 1987; Burkard, Kostaschuk 1995, 1997; etc.) have mentioned the human activities (e.g. cultivation, forest cut and clearing, overgrazing, disruption of natural vegetation cover, constructing, mining, extension of drainage ditches and use of subsurface drainage etc.) as the main reason of gully erosion. Only some authors (Bettis 1983, 1994) have pointed out that gullies are 'native' to uplands and hilly territories. The latter view point is also justified by recent studies (Vanwalleghem *et al.* 2003) which prove that no gully erosion is expected to occur under undisturbed forest vegetation; hence forest gullies that are common to SE Latvia must be recognised as old landscape elements. Recognition of the fact that old gullies are widespread in upland areas of SE Latvia is important because it indicates that gullies are not a unique phenomenon resulting entirely from human agricultural activities. During Holocene at the territory of the Latgale and Augšzeme Uplands, the gully erosion has altered glacial landscape creating in some localities the rugged topography. This process is active and still going on. Currently our knowledge of the factors contributing to gully initiation, particularly about the exact start time of gully formation is very incomplete. To verify conclusions carried out as far as it is necessary to obtain radiocarbon, ^{137}Cs or/and OSL dates.

Analysis of data shows that short non-branched permanent 1st order, sometimes 2nd order gullies are prevailed in upland areas in SE Latvia. In lowland areas of SE Latvia, gullies occur occasionally and are not common feature.

Geological processes caused by gravity, rainfall wash denudation and lateral erosion are still going on and can frequently be observed in gullies, even if the down-cutting process have stopped. The formation of landslides and slumps on the slopes of gullies, the presence of younger V-shaped gullies incised into flat-bottom inactive gullies or *balkas*, as well as other signs testify to the continuing evolution of these landforms.

The principal geomorphological and geological factors that have affected gully erosion in SE Latvia are slope gradient, length, profile form, exposure (aspect), local base level, type and geological structure of outcropped deposits. The complex of these factors has primarily determined the possibility of gully formation, intensity of gully erosion and density of gully network.

The values of gully network density vary from 0 to 0.4 km/km^2 in the localities built up sandy alluvial and glacifluvial deposits to 0.3 to 4.5 km/km^2 in the areas composed of glaciolacustrine clay, stony sandy clayey diamicton and other facies of glacigenic deposits.

The data correlation between the gully network density and the geological structure in this area shows that one of the principal geological factors that determine the gully erosion process and the development of erosion landforms are the infiltration indices of sedimentary rocks, i.e. glacial deposits. The erodibility of glacial deposits is a second-grade factor affecting the gully erosion process in this area.

The densest (more than 2.0 km/km^2) and most intricate gully erosion patterns are common on the slopes of the Daugava River Spillway Valley, in the areas, where this river crosses Baltic Morainic Ridge between the Latgale and Augšzeme uplands. The longest (longer than 1000 m) and the deepest (deeper than 20 m) gullies have developed by leaps during several short reactivation periods alongside the valley formation process and according to the changes in the regional base level of the rivers and the formation of terraces. Most intricate erosion patterns in uplands are determined by the lithostratigraphic sequence. The latter is characterised by alternation of Pleistocene fine to medium glacifluvial deposits covered by stony sandy clayey till. This type of geological structure leads to an increase of erodibility and to the development of gullies as the result of combination of the surface run-off (incision process) and sub-surface run-off (piping process). In the countries with semi-humid temperate climate, e.g. Latvia, the potential susceptibility of an area to erosion could be also related to extreme rainfalls. This climatic factor plays the main role in the formation of gully erosion network. The development of gullies in Latvia could be triggered by intensive snow melting in spring and rainfalls of high intensity (more than 50 mm per 24 h), with recurrence interval 40 to 50 years.

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References

Āboltiņš, O. 1989: *Glaciotectonic structure and glacial morphogenesis*. Riga, Zinātne. 284 pp. In Russian.

Āboltiņš, O. 1994a: Augšdaugava depression. *In* Kavacs G. (ed.), *Nature of Latvia, vol. 1*. Riga, Latvijas Enciklopēdija, 86–87. In Latvian.

Āboltiņš, O. 1994b: Augšzeme Upland. *In* Kavacs G. (ed.), *Nature of Latvia, vol. 1*. Riga, Latvijas Enciklopēdija, 91–92. In Latvian.

Āboltiņš, O. 1995: Latgale Upland. *In* Kavacs G. (ed.), *Nature of Latvia, vol. 3*. Riga, Latvijas Enciklopēdija, 87–89. In Latvian.

Besler, H. 1987: Slope properties, slope processes and soil erosion risk in the tropical rain forest of Kalimantan Timur (Indonesian Borneo). *Earth Surface Processes and Landforms 12*, 195–204.

Bettis, E. A. III. 1983: Gully erosion. *Iowa Geology, Iowa Department of Natural Resources, No 8*, 48–51.

Bettis, E. A. III. 1994: Reflections on Gullies. *In* C.F. Mutel and M. Swander (eds.), *Land of the Fragile Giants: Landscapes, Environments, and Peoples of the Loess Hills*. Iowa City: University of Iowa Press, 30–34.

Blong, R. 1972: Methods of slope profile measurement in the field. *Australian Geographical Studies 10*, 182–192.

Burkard, M.B., Kostaschuk, R.A. 1995: Initiation and evolution of gullies along the shoreline of Lake Huron. *Geomorphology 14 (3)*, 211–219.

Burkard, M.B., Kostaschuk, R.A. 1997: Patterns and controls of gully growth along the shoreline of Lake Huron. *Earth Surface Processes and Landforms 22*, 901–922.

Collison, A., Wade, S., Griffths, J., Dehn, M. 2000: Modelling the impact of predicted climate change on landslide frequency and magnitude in SE England. *Engineering Geology 55*, 205–218.

Dehn, M., Bürger, G., Buma, J., Gasparetto, P. 2000: Impact of climate change on slope stability. *Engineering Geology 55*, 193–204.

Dokuchayev, V.V., 1877: Gullies and their importance. *Journal of Economic Society 3*, 2nd ed., Moscow. In Russian.

Eberhards, G. 1972: *Structure and development of valleys of the Daugava basin*. Riga, Zinātne. 131 pp. In Russian.

Favis-Mortlock, D., Boardman, J. 1995: Nonlinear responses of soil-erosion to climate change - a modelling study on the UK South–Downs. *Catena 25 (1–4)*, 365–387.

Gardiner, V., Dackombe, R. 1977: A simple method for the field measurement of slope profiles. *British Geomorphological Research Group, Technical Bulletin 18*, 9–18.

Goudie, A., Anderson, M., Burt, T., Lewin, J., Richards, K., Whalley, B. and Worsley, P. 1990: *Geomorphological techniques*. London, Routledge (reprint.). 592 pp.

Haigh, M. 1980: Slope retreat and gullying on revegetated mine dumps, Waun Hoscyn, Gwent. *Earth Surface Processes and Landforms 5*, 77–79.

Impacts of Europe's changing climate. 2004: European Environmental Agency briefing No 2/2004, Copenhagen, European Environmental Agency, 27–33.

Lehner, B., Henrichs, T., Döll, P., Alcamo, J. 2001: EuroWasser: Model-based assessment of European water resources and hydrology in the face of global change. Centre for Environmental Systems Research, University of Kassel, Kassel World Water Series no. 5. [Online, 12 October 2006], URL: http://www.usf.uni-kassel.de/usf/archiv/dokumente/kwws/kwws.5.en.htm.

Meirons, Z. 1975: Relief of the Latgale Upland and adjacent regions of Eastern Latvia Lowland. *Reviews of Quaternary Geology 8,* 48–82. In Russian.

Nachtergaele, J., Poesen, J., Wijdenes, D.O., Vandekerckhove, L. 2002: Medium-term evolution of a gully developed in a loess-derived soil. *Geomorphology 46 (3–4)*, 223–239.

Nearing, M.A. 2001: Potential changes in rainfall erosivity in the US with climate change during the 21st century. *Journal of Soil and Water Conservation 56 (3)*, 220–232.

Poesen, J., Boardman, J., Wilcox, B., Valentin, C. 1996: Water erosion monitoring and experimentation for global change studies. *Journal of Soil and Water Conservation 51 (5)*, 386–390.

Poesen, J., Nachtergale, J., Vertstraeten, G., Valentin, C. 2003: Gully erosion and environmental change. Importance and research needs. *Catena 50 (2–4)*, 91–134.

Sidle, R.C., Taylor, D., Lu, X.X., Adger, W.N., Lowe, D.J., deLange, W.P., Newnham, R.N., Dodson, J.R. 2004: Interactions of natural hazards and society in Austral-Asia: evidence in past and recent records. *Quaternary International 118/119*, 181–203.

Stalbovs, R. 1977: Soil erosion in Latvian SSR. Riga, Zinātne, 6-26. In Latvian.

Strods, H. 1992: *History of agriculture in Latvia: from ancient times to XX century.* Riga, Zvaigzne. 287 pp. In Latvian.

Soms, J. 1999: Geological structure of territory as factor controlling the development of gully erosion landforms. *Journal of the State Geological Survey of Latvia 7/99*, 23–27. In Latvian.

Valentin, C., Poesen, J., Li, Y., 2005: Gully erosion: impacts, factors and control. *Catena 63*, 132–153.

Vanwalleghem, T., Van Den Eeckhaut, M., Poesen, J., Deckers, J., Nachtergaele, J., Van Oost, K., Slenters, C. 2003: Characteristics and controlling factors of old gullies under forest in a temperate humid climate: a case study from the Meerdaal Forest (Central Belgium). *Geomorphology 56*, 15–29.

Vanwalleghem T., Poesen J., Nachtergaele J., Verstraeten G., 2005. Characteristics, controlling factors and importance of deep gullies under cropland on loess-derived soils. *Geomorphology 69 (1- 4)*, 76–91.

Zelčs, V. and Markots, A. 2004: Deglaciation history of Latvia. *In* Ehlers J., Gibbard P. L. (eds.), *Extent and Chronology of Glaciations, v.1 (Europe)*. Elsevier, 225–244.