Estonian Journal of Earth Sciences, 2013, **62**, 4, 231–243 doi: 10.3176/earth.2013.17

Landslides and gully slope erosion on the banks of the Gauja River between the towns of Sigulda and Līgatne

Kārlis Kukemilks and Tomas Saks

Faculty of Geography and Earth Sciences, University of Latvia, 10 Alberta Str., LV-1010, Riga, Latvia; Kukemilks.karlis@inbox.lv, Tomas.saks@lu.lv

Received 7 May 2012, accepted 27 August 2013

Abstract. This study examines contemporary and past slope erosion processes in the Gauja River valley and adjoining area between the towns of Sigulda and Līgatne. In the field survey landslides and gullies were mapped. Spatial landslide and gully data were correlated with the landslide- and gully-related features (local relief, slope lithology, slope form, slope angle and density of gullies). A novel approach was applied to establish the relationships between slope processes and factors influencing them. This approach uses correlation between raster values of landslide-related factors in specific slope sections and the number of slope processes in these sections to determine the areas prone to slope processes and their causes. As a result, the susceptibility index of the landslides and gullies was mapped and compared with landslides and gullies from field observations. The map of landslide susceptibility was more compatible with observations from field studies than the map of gully susceptibility. A more developed gully network in the northern part of the study area can be explained by smaller resistance of sediments to erosion, while in the southern part of the study area shallow dolomite deposits are limiting gully erosion. The distributed sediment volumes in separate zones were calculated to compare erosion rates on both banks of the Gauja River. Higher erosion rates were obtained for the left bank. Large cross sections of tributary valleys and large gullies, poorly developed erosional network, weak correlations with slope angle and lithology indicate that the erosion network was formed in a short time interval, possibly during the Late-Glacial period in paraglacial environments.

Key words: Gauja River valley, landslides, gullies, susceptibility mapping, erosion network.

INTRODUCTION

Slope processes have always been in the scope of scientific study (Chen et al. 2001; McCarthy 2002; Lee et al. 2004; Schmidt & Dikau 2004; Valentin et al. 2005; Soms 2006; Kellerer-Pirklbauer et al. 2009; Kohv et al. 2009; Panin et al. 2009). Many studies consider slope processes as a threat to society and the environment. The development of gullies leads to a loss of crop yields and available land (Valentin et al. 2005; Soms 2006). Landslides cause extensive damage to property and occasionally result in loss of life (McCarthy 2002; Lee et al. 2004). Without often discussed negative consequences of gully and landslide erosion, these processes can be considered, from the geomorphological point of view, as a landscape-forming process (Schmidt & Dikau 2004; Kellerer-Pirklbauer et al. 2009; Panin et al. 2009).

Reconstruction of a chronology of erosion events and identification of their causal factors in the past is important for understanding the development of different landforms under the influence of multiple factors (Panin et al. 2009). Moreover, reconstruction of past landscapes helps to identify spatial and temporal dimensions of anthropogenic influences (Kellerer-Pirklbauer et al. 2009).

Independently of the study scope, two different approaches are applied to investigation of slope processes. Slope processes can be considered depending on their spatial location or addressing each process separately. This approach analyses slope processes in relation to location on the terrain, land coverage, precipitation and lithology as different data layers (Lee et al. 2004). The other approach is orientated on detailed morphological, lithological or hydrological analysis of a specified slope fragment. Geotechnical methods of slope stability analysis can also be employed (Chen et al. 2001; McCarthy 2002). Detailed morphometry of gully incisions (Soms 2006) and coring in gully fans (Panin et al. 2009) can be used in reconstructing palaeohydrological conditions.

Landslide susceptibility mapping relies on a complex knowledge of slope movements and their influencing factors (Ayalew & Yamagishi 2005). The process of creating landslide susceptibility maps could be based on qualitative or quantitative approaches (Guzzetti et al. 1999). Qualitative methods rely on expert opinions (Ayalew & Yamagishi 2005; Ayalew et al. 2005).

Quantitative methods are based on numerical expressions of the relationship between triggering factors and landslides (Ayalew & Yamagishi 2005; Ayalew et al. 2005). Quantitative methods can be divided into statistical methodologies and geotechnical models (Xie et al. 2007). The deterministic geotechnical models are based on calculation of mass, energy and momentum (Xie et al. 2007). Due to the need for extensive data from individual slopes, these methods are often effective for mapping only small areas (Ayalew & Yamagishi 2005). The statistical approach uses a predictive function or index derived from a combination of weighted factors (Xie et al. 2007). Landslide susceptibility mapping using either multivariate or bivariate statistical approaches determines coupling between landslide-related factors and spatial distribution of landslides (Guzzetti et al. 1999). Bivariate statistical analyses compare a landslide inventory map with maps of landslide influencing factors in order to rank the related factor classes according to their role in landslide formation. Ranking is normally carried out using landslide densities (Ayalew & Yamagishi 2005). A variety of multivariate statistical approaches exist, but those commonly used to map landslide susceptibility include discriminant analyses and logistic regression (Ayalew & Yamagishi 2005).

Early publications, dealing with slope processes in Latvia, are dated back to the first half of the 20th century. They describe gullies in the Venta, Abava and Daugava River valleys (Delle 1932; Sleinis et al. 1933; Ašmanis 1937). Ašmanis (1937) describes gully incision in new, unaffected areas in the Gauja River valley. Moreover, the rapid gullying process was accompanied by landsliding on the banks of newly developed gullies (Ašmanis 1937). Detailed investigation of slope processes was carried out during the second half of the 20th century. Mostly slope processes were investigated in the Gauja (Āboltiņš 1971; Āboltiņš & Eniņš 1979; Saltupe 1982; Venska 1982; Āboltiņš et al. 2011), Daugava (Eberhards 1972; Soms 2006) and Abava (Veinbergs 1975) River valleys. In recent years detailed investigations of gullies have been carried out in Southeast Latvia (Soms 2006). Nonetheless there are many insufficiently investigated questions including the development time (Soms 2006) and conditions of landslides and gullies. In the Gauja River valley only one gully has been absolutely dated (Saltupe 1982). No absolute datings of landslides are available. Moreover, many poorly constrained questions still exist, like slope process–groundwater–climate coupling, their interactions with gullying, landsliding and suffosion processes.

In the year 2002 more public attention was paid to landslide processes in Latvia, because a heavy landslide occurred in the Turaida Castle mound. The Turaida Museum Reserve and medieval castle in the vicinity of Sigulda are popular tourism destinations in Latvia. Two landslides occurred in the Turaida Castle mound, causing threat to the historical building and blocking the local road from Turaida to Sigulda. Detailed investigation of the Turaida landslide and slope stabilization measures were carried out (Āboltiņš et al. 2011), however, national- and/or regional-scale landslide databases would be a useful tool for zoning and management of potential landslide risks (Van Den Eeckhaut & Hervás 2012).

The scope of this study includes the investigation of the spatial distribution of landslides and gullies in the Gauja River valley between Sigulda and Līgatne and determination of their related factors. The landslides and gullies are treated as landscape-forming processes, by using spatial approach analyses of their distribution, and the factors influencing gully and landslide formation and their timing are determined. The term ‘landslide’ incorporates a wide variety of processes that result in the downward and outward movement of slope-forming materials. The materials may move by falling, toppling, sliding, spreading or flowing. Such a wide variety of processes was chosen because different morphological forms and development stages of landslide processes are present in the study area, alternating from fresh landslides with high topographic expression till to old, eroded slides with poorly preserved morphological characteristics. Weak topographic expression of old landslides complicates their allocation according to the sliding mechanism, without detailed morphological and lithological analysis.

AREA DESCRIPTION

The study site is located in Central Latvia within the area glaciated by the Scandinavian ice sheets during the last Ice Age (Zelčs et al. 2011) and stretches along the northwestern foot of the Vidzeme upland (Fig. 1). The region between the towns of Sigulda and Līgatne was selected for study due to an abundant gully erosion network and presence of many landslide events. In the vicinity of Nurmiži, 8 km upstream from Sigulda, the highest density of the gully erosion network in Latvia (2.2–2.4 km/km^2) has been estimated (Āboltiņš 1995). Other landscape-forming processes like landslides and suffusion incisions, formed by discharge of groundwater preferential flow routes, are present.

The present-day topography of the study area (Fig. 2) has largely been formed as a result of Pleistocene glaciations, particularly of the last Weichselian event (Zelčs & Markots 2004). The ice sheet retreated from this territory northwards during late glacial time. Due to inclination of the land surface from the Vidzeme upland towards the retreating ice margin, meltwaters could not drain freely, forming ice-dammed lakes along the ice

Fig. 1. Location of the study area.

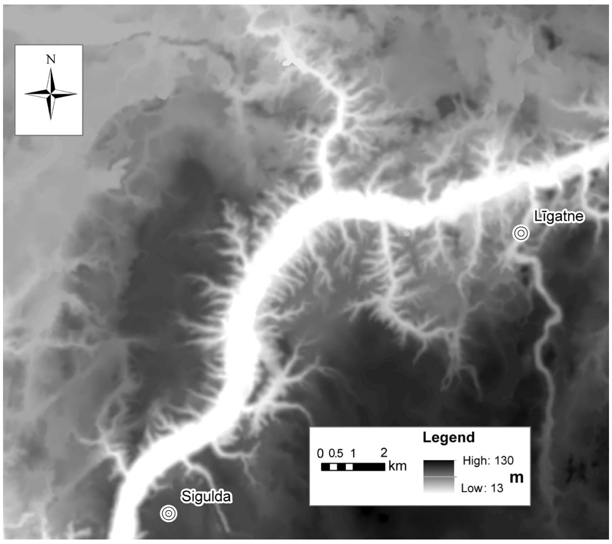

Fig. 2. Digital terrain model of the study area (processed from Jarvis et al. 2008).

margin. Drainage of the ice-dammed lakes was often a catastrophic process (Zelčs & Markots *ibid.*). As a result, in watershed areas deeply-incised (up to 70 m in the vicinity of Sigulda) proglacial spillways were formed (Zelčs & Markots *ibid.*).

The study area has a temperate, humid semi-continental climate with mean annual temperature in January of –5 to –6 °C and +17 °C in July and average annual precipitation of 700–800 mm (Kalniņa 1995). Middle and Upper Devonian sandstone, siltstone, clay and dolomite outcrop on the slopes of the Gauja River valley (Fig. 3). Carbonate and sulphate rocks (dolomite, dolomite with marl and gypsum interlayers) occur only in a narrow zone in the vicinity of Sigulda. An up to 30–40 m thick layer of Quaternary deposits, mainly glacial till, overlies the bedrock (Āboltiņš 1971).

The Gauja River valley has no common system of terraces but four separate systems (Āboltiņš 1971). In slopes of the deeply dissected valley groundwater discharge takes place. Flowing groundwater sustains steady gully incision and consequently additional supply of groundwater (Āboltiņš & Eniņš 1979). Furthermore, glacioisostatic rebound and sea-level changes lowered the base level during the Holocene, favouring gully incision. The length of the gullies varies from 500 m to 3 km, depth from 5 to 60 m (Āboltiņš & Eniņš 1979). Nowadays gullies in the study area are mostly passive with abundant vegetation cover (Venska 1982), while landslide processes are still present. In the year 2002 a landslide occurred on the slopes of the Turaida castle mound, however, its possible anthropogenic causes are widely discussed (Āboltiņš et al. 2011). Landslide processes are considered as one of the gully triggering mechanisms in the Gauja River valley (Venska 1982). According to Venska (1982), the landslide cirque gullies can be formed depending on the slope composition and preferred groundwater discharge locations. Gullies in the study area have typical u-shaped cross sections. They are under permanent vegetation cover (Āboltiņš & Eniņš 1979) and can be classified as bank gullies (Poesen et al. 2003). Only some side branches are still active and have v-shaped cross sections. In the study area the gully erosion network mostly has a dendritic pattern (Āboltiņš & Eniņš 1979).

MATERIAL AND METHODS

The ESRI ArcGIS 10 software was extensively used for spatial analysis and visualization of the results. In order to create a detailed geomorphological map of the study area, a field survey was combined with the analysis of large-scale topographic maps stored at the depository of maps of the University of Latvia and the Shuttle Radar Topography Mission (SRTM) digital terrain model (Jarvis et al. 2008). Comparing cross sections of the river valley, created with the SRTM digital terrain model and large-scale topographic map (Fig. 3), we can observe a higher resolution of the data derived from the topographic map. However, digital terrain models have many advantages, like simple data processing, in comparison with topographic maps. The SRTM digital terrain model has been developed from raster data with the 90 m size of the resolution element. These data have been corrected with orbit tracks on higher resolution with

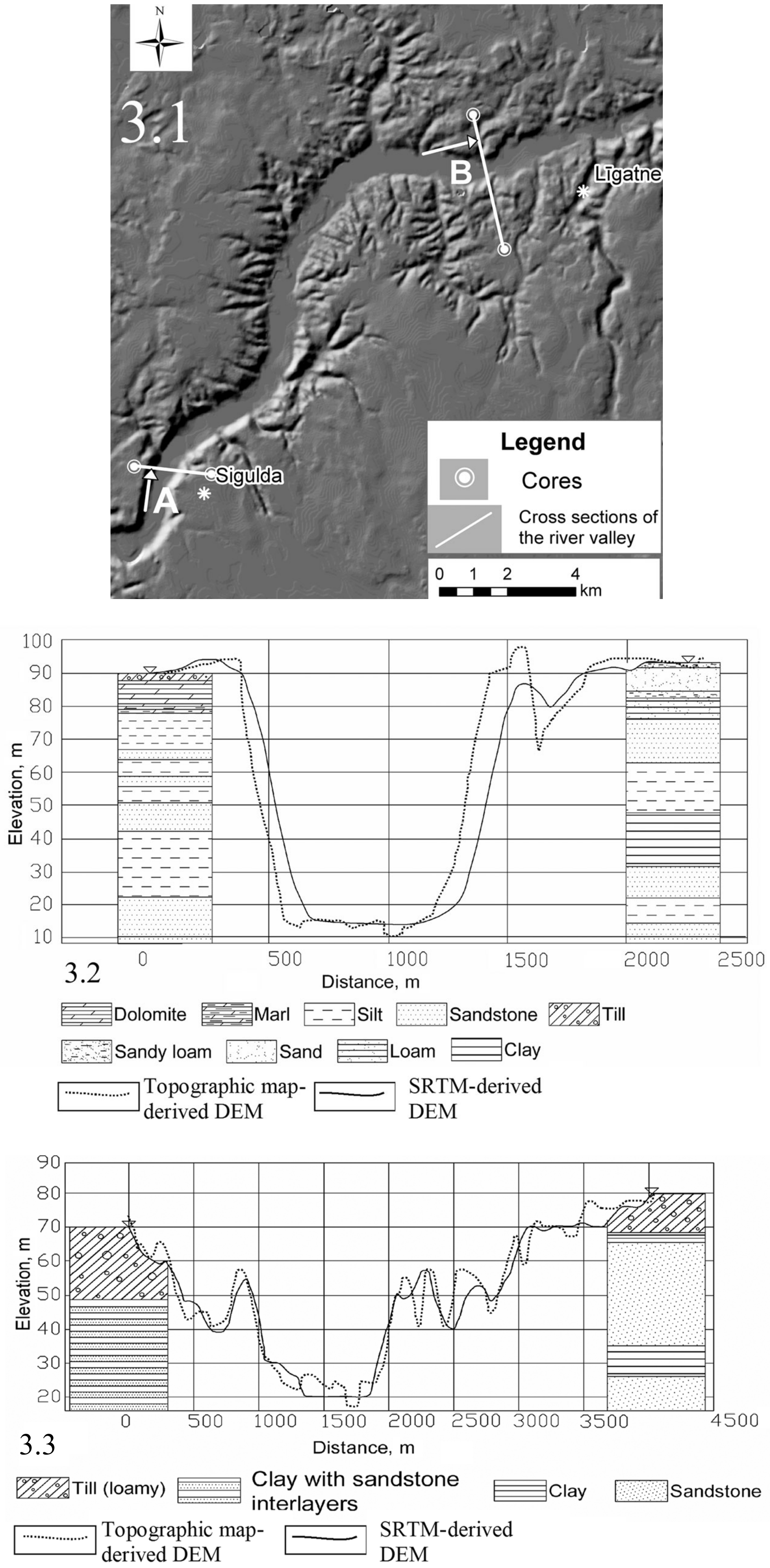

Fig. 3. Location of both cross sections in the study area (3.1). Cross sections A (3.2) and B (3.3) with comparison of SRTM- and topographic map-derived digital elevation models (DEM), and typical geological settings of the study area.

the element size of 30 s. During research the original resolution and smoothed SRTM (Jarvis et al. 2008) digital terrain model were applied. The original resolution data have a 25 m cell size in the areas of the X band coverage, but smoothed data have cell sizes of 250 m.

At first landslides and gullies were identified from 1 : 10 000 topographic maps and mapped as different layers in ESRI ArcGIS 10. The identification of landslides on a topographic map was based on the recognition of topographic elements associated with landslides. Characteristic features of landslides are the presence of a clear main scarp, an abrupt change in the slope and a stepped topography (Van Den Eeckhaut et al. 2005). The landslide cirque is a typical morphological characteristic of landslides important in distinguishing them from other tongue-shaped morphological forms of slopes like remnants of river terraces. The identification of gullies was based on the technique described in Soms (2006). The landslides and gullies were mapped as points in different vector data layers shown in Fig. 4.

During the field survey the study area was inspected for the occurrence of landslides and gullies and their positions were mapped with the GPS *Magellan explorist 400*. Field survey was carried out along both banks of the Gauja River valley. All landslides and gullies were described directly on the field. The smallest landslide had a 1.5 m wide main scarp and reached 2.5 m in length downhill, the smallest gully had a 1 m deep incision and stretched upslope for about 4 m. Earth slides were divided in translation and rotation slides according to Hutchinson (1988), trying to identify their freshness and state of preservation of the typical landslide characteristics. Gullies were characterized according to their size as large and small, according to activity as active and passive and according to the form of the cross section as u- or v-shaped (Soms 2006). Moreover, the shape of gullies can be complex, with a u-shaped cross section of the main channel and v-shaped side branches. Old, strongly eroded landslides were poorly distinguishable from earth flows during the visual interpretation due to their similar morphological characteristics. Nonetheless, large abundance of different slope processes and their development stages made their allocation in separated groups difficult. Therefore, classification of landslides according to the sliding mechanism could be possible after detailed investigation of their morphology and lithology. For statistical and spatial analysis landslides were treated as a single group, while gullies were divided into large and small, respectively. The gullies were considered as large when those could be clearly identified on topographic maps at a scale of 1 : 10 000, while small gullies were described during the field work.

In total, 231 landslides and 259 gullies were mapped in the course of the field survey, but only 37 landslides and 84 gullies were mapped from 1 : 10 000 topographic maps (Table 1). The landslides identified from the topographic maps were verified with known landslide locations. Using the ESRI ArcGIS 10 tool *Buffer*, a 150 m buffer zone around all cartographically determined landslides was constructed. The landslides from the field survey within the 150 m buffer zone were determined. In 23 cases from 37 one or more landslides during the field survey were found in a 150 m buffer zone around cartographically identified landslides. A 150 m buffer zone was chosen because the location of the landslide could be measured in different places and the GPS error

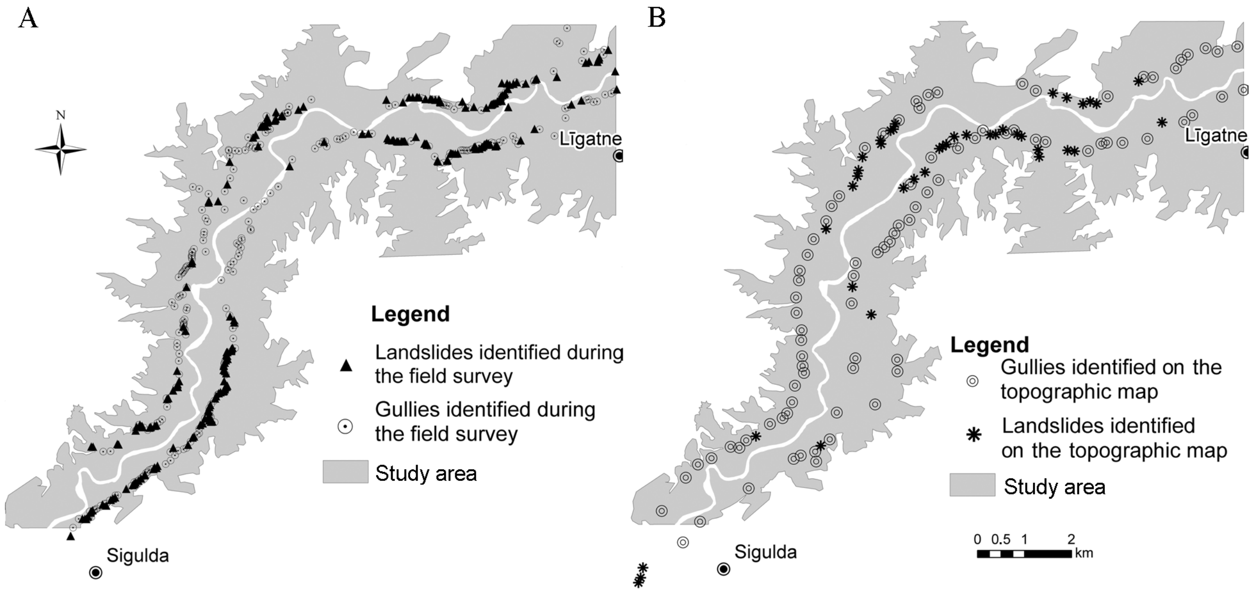

Fig. 4. Landslides and gullies identified in the study area from the field survey (A) and on 1 : 10 000 topographic maps (B).

Table 1. Landslides and gullies identified from the topographic maps and during the field survey on the banks of the Gauja River

Source	Landslides		Gullies	
	Right bank	Left bank	Right bank	Left bank
Field survey	104	127	127	132
Topographic maps	17	20	40	44

was considered. The *Monte Carlo* method (Sobol 1994) was used to determine how many cases of landslides could be found by chance in a 150 m buffer zone around 37 cartographically determined landslides. In this case the *Monte Carlo* method was applied to generate a set of random points allowing comparing the spatial distribution of slope processes in the study area with random distribution. Using the ESRI ArcGIS 10 tool *Create Random Points*, 231 random points (equal with the number of landslides mapped in the field) were generated in the study area. In 12 cases random points were found in a 150 m distance around cartographically determined landslides.

Potential landslide-related factors, such as gully density, slope height, clay content, slope angle and slope profile curvature, were chosen to prepare the landslide susceptibility map. Gully density was calculated from the field survey results using the *Kernel Density* tool with the cell size of 25 m and search radius 250 m. Slope angles of the study area were calculated from the SRTM (Jarvis et al. 2008) digital terrain model with the ArcGIS 10 tool *Slope*. Clay content in slope-forming deposits is widely recognized as a landslide-related factor (Jumiķis 1964; Kohv et al. 2009). The lithology of the study area was determined from boreholes (Takčidi 1999). The boreholes located on the valley banks within a 3 km distance from the slope were selected. The clay content (N_m) of the borehole lithology was calculated (Eq. 1) for the interval (h_u) between the top of the borehole and water level of the Gauja River:

$$N_m = \frac{h_m}{h_u}, \tag{1}$$

where h_m is the thickness (in metres) of all clay- and silt-containing deposits in the interval.

The clay content of each borehole was calculated and added to the attribute data of ESRI ArcGIS 10 shapefile. The Inverse Distance Weighting, Natural Neighbour and Kriging methods were used for interpolation of the clay content in the study area.

Relative slope height was considered as a landslide- and gully-related factor as well. Relative height was attained using the ESRI ArcGIS 10 tool *Minus* subtracting the horizontal plane coinciding with the maximal river water level from the SRTM (Jarvis et al. 2008) terrain model. An additional factor, which is related to increased landslide susceptibility, is slope profile curvature. Slope curvature was used by Lee et al. (2004) as a landslide-related factor to map landslide susceptibility in the Korean Peninsula. Upwardly concave slope curvature was associated with higher landslide susceptibility (Lee et al. 2004). To prove the statement, slope profile curvature was calculated with the ESRI ArcGIS 10 tool *Curvature* from the digital terrain model. The values of slope profile curvature in landslide point locations were determined with the ESRI ArcGIS 10 tool *Extract values to points*. The results show that landslides are more frequently found in convex curvature than in random points, contrary to the study of Lee et al. (2004). Therefore slope curvature was not considered as a relevant landslide-related factor. The method with 231 random point sampling, mentioned before, was used to prove the relevance of other landslide-related factors too. Such factors as gully density, clay content and slope angle were justified with higher values in landslide locations than in random points and were investigated in detail.

A proximity index, inspired by landscape design (Gustafson & Parker 1994), which quantifies the spatial context of the slope process distribution in relation to its neighbours, was applied to determine the spatial distribution of landslides and gullies. In horizontal projection of the valley slope plane two groups of 231 and 259 random points were generated in four separate runs. The distances between landslides, gullies and random points using the tool *Point distance* were found. The ESRI ArcGIS 10 tool *Point Distance* calculates distances from the first specified layer of points to the second within a specified 400 m search radius.

A novel approach for analysis of the location and spatial distribution of a slope process was developed to create a landslide susceptibility map. Our study uses a specific statistical approach to carry out a GIS-based landslide susceptibility zoning. This approach can be applied in case of landslide clustering along narrow strips, e.g. slopes of a river valley. Initially a control group of 35 landslides was randomly selected from the entire landslide data set. The rest 196 landslide events were projected on their trendline where the landslide-related factors are sampled from the raster data. Consequently, data are sampled in the locations with the highest landslide density without major influences of adjacent areas. In contradiction to most of the statistical methods, this approach determines the number of slope processes in separate sections and correlates them with the average value of the factors related to the slope process in the corresponding sections. Therefore, the user can analyse the characteristic values of each section separately and compare them with other sections.

At first landslide coordinates were depicted in the MS Office Excel chart as x, y data. To coordinate points a polynomial trendline of sixth order was applied. In the next step the trendline was imported in AutoCad 2007 and separated in 250 m long sections. For each section a projection area was constructed (Fig. 5B).

A line with section division was imported in ESRI ArcGIS 10 (Fig. 5A). The centre points of sections were drawn in a separate shapefile. The number of landslides and gullies was counted in each section and written in the MS Office Excel worksheet. Raster values of the slope angle, clay content, relative height and gully density were sampled in centre points of the sections. Sampling was carried out for original raster data with the cell size of 25 m and smoothed data with the cell size of 250 m to diminish the influence of accidental values. The sampled data was exported to MS Office Excel. The sampled raster values of the centre points were correlated with the number of landslides and gullies in each section. The PASW Statistics 18 software was applied to calculate correlation coefficients. Spearman's rank correlation was calculated, because source data were not normally distributed. The weights, derived from correlations, were used for mapping the landslide susceptibility.

The Landslide Susceptibility Index (LSI) according to Lee et al. (2004) was calculated by summation of each factor's value (F_v) multiplied by each factor's weight (F_w), equal with the correlation coefficient (see Eq. 2):

$$\mathrm{LSI} = \sum 10 F_w F_v . \tag{2}$$

The ESRI ArcGIS 10 tool *Weighted Sum* was applied to landslide susceptibility mapping. Moreover, all ranges of raster values were reclassified in the same scale from 1 to 3. The calculated correlation coefficients between the number of landslides or gullies in the sections and landslide-related factors were used as weights and multiplied with reclassified factor values. The landslide susceptibility map was created with three landslide susceptibility classes. The classes were defined using the Natural Breaks method available in ESRI ArcGIS 10. This method defines classes by grouping similar values and maximizing differences between them. The boundaries of the classes are set where the differences between the values are relatively important. A control group of 35 landslides was used

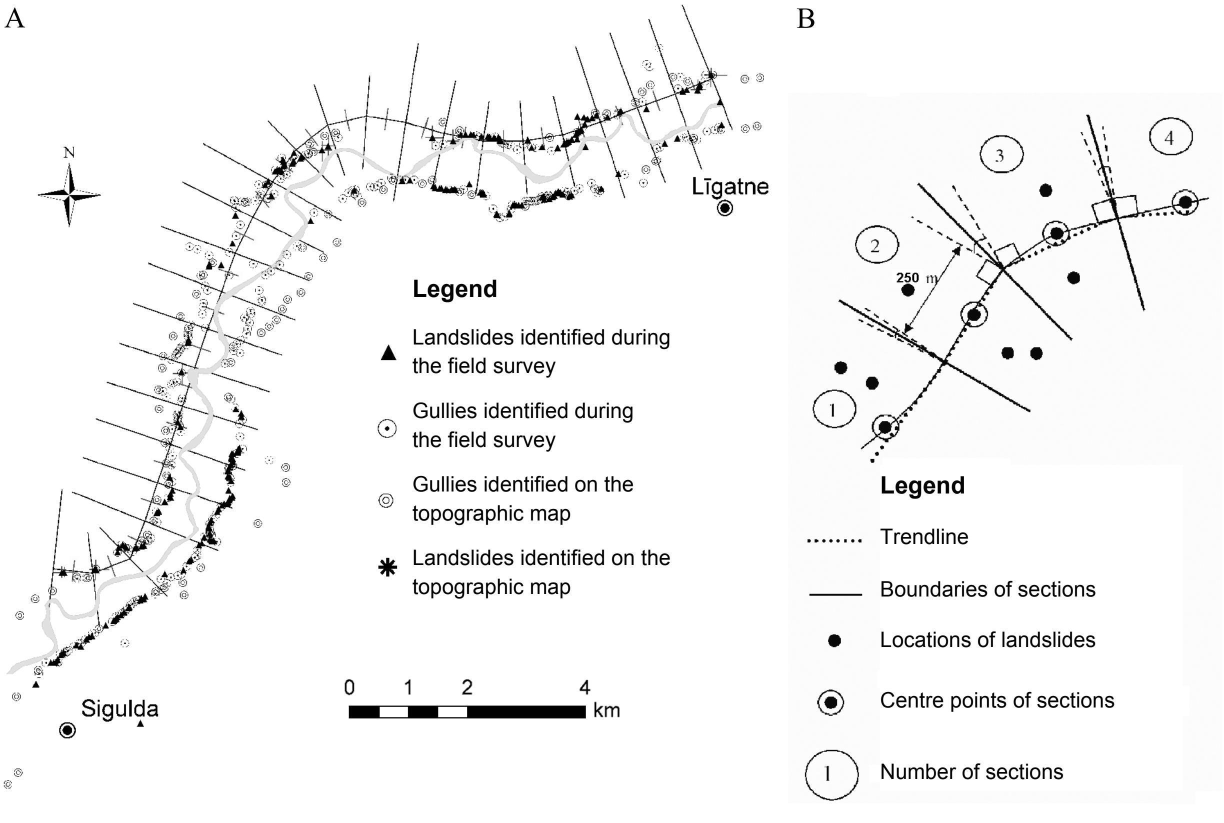

Fig. 5. Division of the right bank area in 250 m long sections (A). Construction of a projection area (B).

for verification of susceptibility zoning. Verification was carried out by comparing raster values in the locations of the control group with raster data from locations of 1000 random points.

So far we have discussed methods used for analysis of contemporary slope processes, but we attempted to reconstruct initial slopes from the best-preserved geomorphological forms as well. The slopes of the Gauja River valley as we see nowadays have been subject to intensive erosion and deposition processes. The morphology of the river valley has largely been sculptured by glacier meltwater, which complicates the reconstruction of the slope morphology before the erosion by gullies and landslides. Less eroded and well-preserved fragments of the slopes were chosen and marked with separate points in the ESRI ArcGIS 10 shapefile. Absolute height was added to these points as attribute data. Selected point data were used to construct a conditional model of the initial terrain. The volumes of transported sediments were calculated using the ESRI ArcGIS 10 tool *Cut Fill*. By taking two terrain models, the tool *Cut Fill* calculates volumes of surface material removal, surface material addition and areas where the surface has not changed. Both the initial and contemporary terrain rasters were divided in four 2 km wide zones (Fig. 6). The area of calculations was extended about two times to diminish the influence of accidental errors. Typical accidental errors could be relatively large tributary valleys (for example the Brasla River valley) dissecting the slopes of the Gauja River valley, which are not representative of slope processes acting on the slopes of the main river channel.

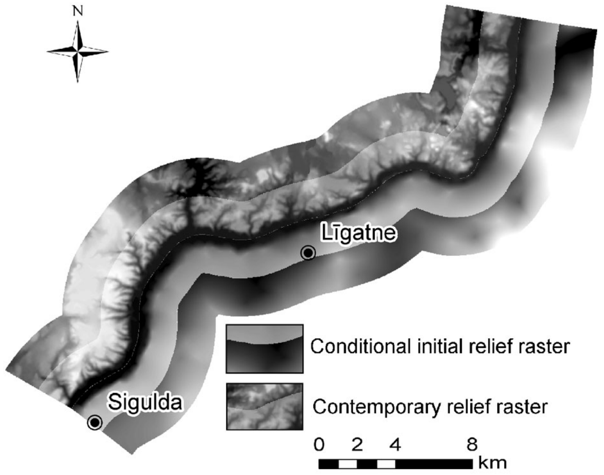

Fig. 6. Division of the study area into four zones of conditional initial (left bank side) and contemporary (right bank side) relief rasters (processed from Jarvis et al. 2008).

RESULTS AND INTERPRETATION

Figure 7 shows the whiskers plot, average distance and standard deviation between landslides, gullies and random points in 400 m distance around point locations in the study area. The differences of median between the landslide, gully, random gully and random landslide groups were tested using the Wilcoxon–Mann–Whitney nonparametric test with 95% confidence interval, because the data do not follow a normal distribution. Null hypothesis was rejected as the asymptotic significance in all cases was 0.00, indicating that the difference between medians of groups is important and statistically significant. The Wilcoxon–Mann–Whitney test compares medians of two data sets and can be efficiently applied to non-normal distributed data (Conover 1980).

Distances between randomly generated points tend to be longer than between landslides and gullies from field studies (see Fig. 7). An average distance of 191.59 m between landslides indicates clustering in comparison with 244.76 m between the same number of random points. Similarly, gullies indicate weaker clustering (212.20 m) compared with the same number of random points (232.81 m). Distances between landslides and gullies, located on steeper slopes, are not different from rest of the gullies and landslides. Consequently, the clustering of landslides and gullies indicates the presence of possible slope process-related factors. Such factors were determined by correlating the number of landslides or gullies in the slope section with different raster data layers.

Correlating the spatial distribution of slope processes with their related factors (see Table 2), the highest correlation was found between landslides and the slope angle (0.46). Landslides also have significant correlations with gully density and relative height of the slope. One possible explanation for the importance of relative height could be the variety of different layers outcropping in higher slopes, including clays, silts and sandstones. Another

Table 2. Spearman's correlation between the number of landslides and gullies in sections and their related factors

Landslides discovered in field survey				
Gully density	Relative height of the slope	Clay content (*Natural Neighbour*)	Clay content (*Kriging*)	Slope angle
0.31*	0.34*	0.12	−0.09	0.46*
Gullies discovered in field survey				
–	0.17	−0.18**	−0.19**	0.14

---

* Correlation is significant at the 0.01 level.

** Correlation is significant at the 0.05 level.

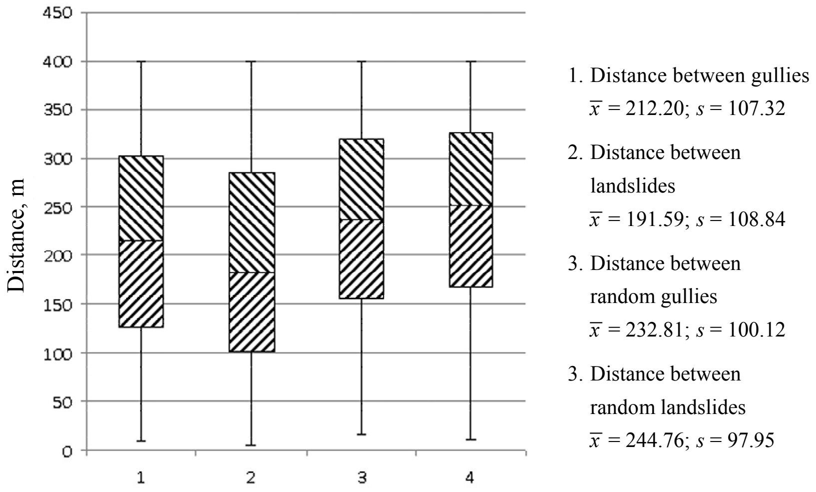

Fig. 7. Whisker plot displaying median, 25th percentile, 75th percentile, minimum and maximum of six data sets. On the right side of the plot an arithmetical mean ($\overline{x}$) and a standard deviation (s) of data sets are displayed.

Table 3. Calculated sediment volume transport from slopes of the Gauja River valley

The 2 km zone, including the slope						
Right bank slope (RS2), m^3	Left bank slope (LS2), m^3	Total (RS2 + LS2), m^3	Proportion of the right bank slope (RS2/Total)	Proportion of the left bank slope (LS2/Total)	Difference between both bank slopes (LS2 – RS2), m^3	Difference/Total, %
561 284 130	632 943 500	1 194 227 630	0.47	0.53	71 659 370	6.0
Distant 2 km zone, excluding the slope						
Right bank slope (RS4), m^3	Left bank slope (LS4), m^3	Total (RS4 + LS4), m^3	Proportion of the right bank slope (RS4/Total)	Proportion of the left bank slope (LS4/Total)	Difference between both bank slopes (LS4 – RS4), m^3	Difference/Total, %
449 147 710	559 977 190	1 009 124 910	0.45	0.55	110 829 480	10.98

explanation could be a buttressing effect of the toe of the slope for shorter slopes. The correlation coefficients calculated from original resolution data tend to be higher than from smoothed data, therefore correlations from smoothed data will not be considered in detail.

The correlation of clay content with landslides strongly depends on the interpolation method applied. Insignificant positive correlation between landslides and clay content was found only when *Natural Neighbour* interpolation was applied. Independently of the interpolation method applied, there was a negative correlation between gullies and clay content. This negative correlation can be explained with higher erosion resistance of clay-containing sediments. The slope curvature was excluded from the correlation analysis, because no correlation was found. The large gullies, identified from topographic maps, did not indicate significant correlations with related factors, therefore their correlations were not investigated in detail.

The landslide susceptibility was mapped by applying the following landslide-related factors and their weights taken from Table 2 multiplied by the coefficient 10 (see Eq. (2)):

1. gully density: 3.1;
2. relative height of the slope: 3.4;
3. slope angle: 4.6.

The transported sediment volumes of both valley sides were estimated to determine possible differences of erosion rates depending on the bank of the river. The transported sediment volumes were calculated in 2 km wide zones on both sides of the valley to estimate possible sediment volume differences in relation to the distance from the valley centre. Calculation was performed for each zone separately (Fig. 6).

Table 3 shows rather similar proportions for the left and the right bank slope (0.53 and 0.47) in the near 2 km zone, but discrepancy increases with the distance from the valley centre until 0.55 and 0.45 in the distant zone. Sediment volumes calculated in the 2 km zone from the valley centre characterize erosion rates on the slope and in short gullies, but the volumes calculated in a distant 2 km zone characterize the erosion rates of long gullies and tributaries (Fig. 6).

DISCUSSION

During the field studies a great variety of morphological forms of gullies and landslides were found, for example, rotation and translation slides and slides in different development stages. Furthermore, erosion forms can be altered significantly in the course of time, which makes their identification during the field surveys more difficult. Consequently, the classification of slope processes was carried out under conditions of gross simplification. In the study area zones with higher or lower landslide and gully activity have been recognized. The morphology of the observed gullies and landslides varies very significantly also in the study area.

An analysis of the distribution of the slope processes revealed a high concentration inside the landslide group (Fig. 7). At 400 m distance around each of the 231 landslides the average distance between landslides is 191.59 m, which indicates clustering in comparison with 244.76 m between the same number of random points. Similarly, gullies indicate a weaker clustering (212.20 m) compared with the same number of random points (232.81 m). Some possible explanations for internal concentration of the landslide and gully groups could be related to time-transgressive development of the slope processes. The time as an acting factor characterizes the development stage of the slope processes. For example, a landslide exposes the underlying material and triggers subsequent gully erosion. Nonetheless, correlation analysis of landslide and gully-related factors revealed significant genetic differences between both slope processes. Different landslide and gully-related factors, shown in Table 2, were revealed.

The landslide susceptibility map (Fig. 8) was verified using a control group of 35 landslides identified during the field survey. In landslide point locations raster values of the landslide susceptibility map were sampled, yielding the average value of 1.65. Then, raster values in 1000 random point locations were sampled and the average value of 1.40 was calculated. The landslide susceptibility map also allows predicting landslide locations with 16% higher probability than by chance. The results of the gully susceptibility mapping were not concordant with the data from the field survey. Possible explanations for such discrepancy could be lack of appropriate gully-related factors. Furthermore, gullies dramatically change landscape around them. Therefore the point of gully initiation cannot be used for the identification of a gully at its later development stages. Moreover, gully location cannot be reduced to one point.

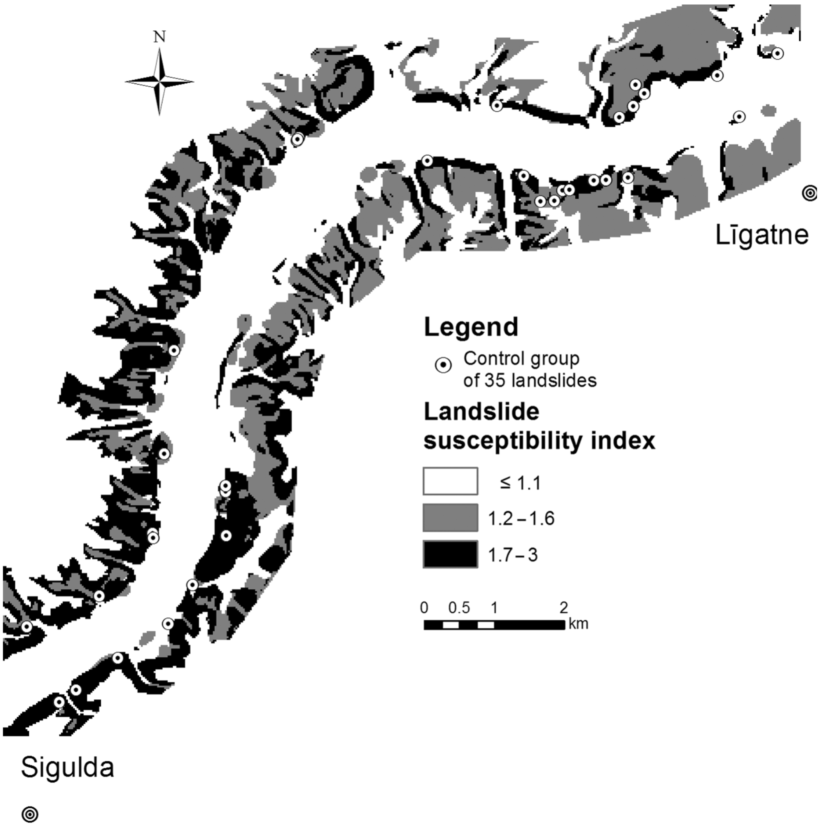

Fig. 8. Landslide susceptibility map.

Surface lithology is a critical factor controlling gully initiation and development in the study area. In territories where dolomite is exposed near the surface the gully network is less developed and the main gully incision is not accompanied by side gullies. On the contrary, in landscapes with less surface erosional resistance (e.g. sandstones) the gully network is more developed with braided channels and a dendritic drainage pattern (Fig. 9).

The estimated ratio of eroded volumes shows that the specific weight of the left bank gully and tributary eroded volumes increases with the distance from the valley centre. A possible explanation could be a deeper base level of the left bank zones. Consequently larger sediment volumes were eroded. It can be speculated that the higher erosion rates in the left bank zones could be related to drainage of ice-dammed lakes from the upland during Late-Glacial time. Nonetheless, these data should be treated with caution because SRTM-derived DEM has low resolution and can contain various sources of errors.

The development of the Gauja River valley gully network is poorly constrained. The radiocarbon datings by Saltupe (1982) in the study area revealed an age of 4620±60 ^{14}C years BP in the base of the gully fan and 4470±70 ^{14}C years BP in the middle section of the gully fan. These dating results can be attributed to the Subboreal chronozone (Saltupe 1982). The age of the gully erosional network has been dated using the terrace sequence of the Gauja River valley too. Large gully fans are dated according to underlying terrace levels that have been formed during the Younger Dryas (Āboltiņš 1971). The development of large and deeply incised gullies in the Daugava River valley have been attributed to drainage of the ice-dammed lakes from the upland areas (Eberhards 1972). Intensive drainage of ice-dammed lakes and formation of proglacial spillways were common for Bølling and Older Dryas time in Latvia when main slope-forming processes could take place in the Gauja River valley (Āboltiņš & Eniņš 1979; Venska 1982).

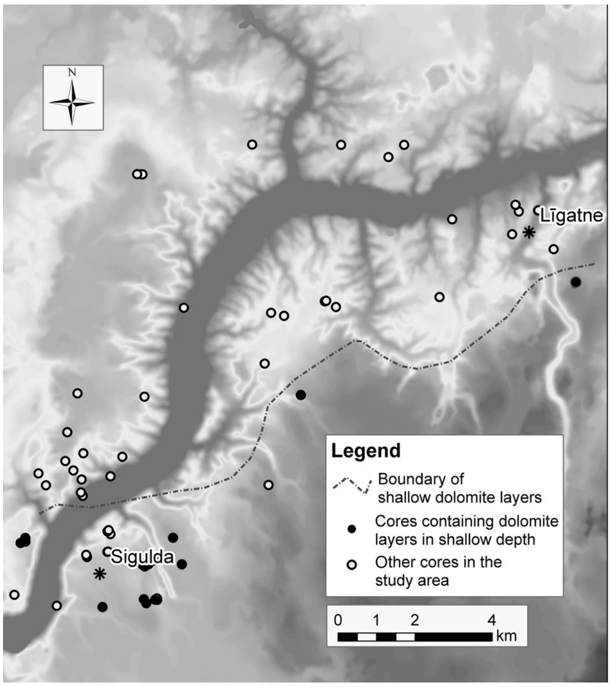

Fig. 9. Structural control of shallow dolomite layers observable in the gully network. Elevation raster data derived from Jarvis et al. (2008). Location of boreholes according to Takčidi (1999).

Large and small gullies have no common spatial locations and related factors: large gullies do not correlate with gully-related factors. Studies, done in Southeastern Latvia (Soms 2006), give an insight into the palaeoclimatic conditions of gully development. According to these studies, huge cross sections of gullies are not comparable with precipitation during the Holocene (Soms 2006). A possible explanation for non-typical morphology of large gullies is their development in paraglacial conditions (Ballantine 2002) during the end of the last Ice Age (Soms 2006). The drainage of ice-dammed lakes from the upland areas or meltwater directly from dead ice could incise large gullies simultaneously with the development of the main river channel. The Gauja River dropped suddenly in the span between the towns of Sigulda and Līgatne (Āboltiņš 1971). Supposedly that could cause high discharge and deepening of the base level, resulting in rapid afflux from adjacent territories and intensive gully incision. Moreover, rapid stream incision in glacier-compacted sediments (Easterbrook 1999) could expose steep, unstable slopes and act as an erosion-promoting factor.

Erosional processes could have reactivated during the Holocene due to rare but heavy rainstorms, large snow storage and high snowmelt runoffs. Forest clearing and land use in agriculture, river bank erosion and slope undercutting could have been responsible for higher regional erosional rates.

In trying to predict the future scenarios of slope evolution in the Gauja River valley, climate change should be considered. Climate sensitivity of the landscape is a complex characteristic, connected to local geomorphological and hydrological controls as well as climatic change (Schmidt & Dikau 2004). According to the report of the ENSAMBLES project (van der Linden & Mitchell 2009), it can be estimated that annual precipitation in the Gauja River basin in 2021–2050 relative to 1961–1990 will increase by 8–12%. The effects of possible precipitation change on slope processes in the Gauja River valley are the subject of further research. Increase in precipitation can trigger landslides because water reduces the stability of clayey deposits considerably. Moreover, the sediment sequence in the study area is prone to slope failures under climate change. Location of permeable sandstone layers (prone to groundwater rise) above clayey layers, increases slope failure probability with respect to precipitation increase.

CONCLUSIONS

In total, 231 landslides and 259 gullies were discovered during the field survey in the study area. The topographic map of the scale of 1 : 10 000 proved to be an inappropriate source for identifying landslides because only 23 from cartographically determined landslides were found during the field survey.

Landslide prone areas were detected during data analysis. The variability of landslide susceptibility in the landscapes of the Gauja River valley can be expressed by landslide-related factors. The landslide-related factors, which were found to be relevant in the study area, are slope angle, gully density and relative height of the relief. The gully-related factor is sediments without clay and possibly relative height of the slope.

Smoothed raster data did not indicate higher correlations with gullies and landslides. The landslide-related factors were used for landslide susceptibility mapping. The landslide susceptibility map allows predicting landslide locations with 16% higher probability than by chance.

A typical dendritic gully erosion network of the study area was formed due to specific morphological, lithological and palaeoenvironmental characteristics in this span of the Gauja River valley. Large gullies in the study area possibly developed during the Late-Glacial as a result of paraglacial adjustment. During this time drainage of ice-dammed lakes from the upland areas or meltwater directly from dead ice could erode large gullies synchronously with the development of the Gauja spillway valley.

Higher erosion rates in the left bank areas can be explained by a deeper base level or drainage of ice-dammed lakes from the upland areas.

Acknowledgements. We would like to thank the people who provided us with scientific and practical support during the research process. We are grateful to our referees, especially Professor Vitālijs Zelčs who helped us to improve our publication significantly, and to Māris Nartišs who provided technical support in GIS.

REFERENCES

Āboltiņš, O. 1971. *Razvitie doliny reki Gauya* [*Development of the Gauja River Valley*]. Zinātne, Riga, 104 pp. [in Russian].

Āboltiņš, O. 1995. Gaujas senleja [Gauja Ancient Valley]. In *Latvijas daba 2. sēj.* [*Nature of Latvia, 2. Band*] (Kavacis, G., ed.), p. 101. Latvijas Enciklopēdija, Rīga [in Latvian].

Āboltiņš, O. & Eniņš, G. 1979. *Gaujas senieleja* [*Gauja Ancient Valley*]. Liesma, Rīga, 134 pp. [in Latvian].

Āboltiņš, O. P., Mūrnieks, A. & Zelčs, V. 2011. Stop 2: The River Gauja Valley and landslides at Sigulda. In *Eighth Baltic Stratigraphical Conference. Post Conference Field Excursion Guidebook* (Stinkulis, Ģ. & Zelčs, V., eds), pp. 15–20. University of Latvia, Rīga.

Ašmanis, K. 1937. *Gauja. Sērija 'Jaunais zinātnieks'* [*River Gauja. Series 'New Scientist'*]. Valters un Rapa, Rīga, 75 pp. [in Latvian].

Ayalew, L. & Yamagishi, H. 2005. The application of GIS-based logistic regression for landslide susceptibility mapping in the Kakuda-Yahiko Mountains, Central Japan. *Geomorphology*, **65**, 15–31.

Ayalew, L., Yamagishi, H., Marui, H. & Kanno, T. 2005. Landslides in Sado Island of Japan: Part II. GIS-based susceptibility mapping with comparisons of results from two methods and verifications. *Engineering Geology*, **81**, 432–445.

Ballantine, C. K. 2002. Paraglacial geomorphology. *Quaternary Science Reviews*, **21**, 1935–2017.

Chen, Z., Wang, J., Wang, Y., Yin, J. H. & Haberfield, C. 2001. A three-dimensional slope stability analysis method using the upper bound theorem, Part I: theory and methods. *International Journal of Rock Mechanics & Mining Sciences*, **38**, 369–378.

Conover, W. J. 1980. *Practical Nonparametric Statistics*. John Wiley & Sons, New York, 493 pp.

Delle, J. 1932. *Venta un Abava. Sērija 'Jaunais zinātnieks'* [*River Venta and River Abava. Series 'New Scientist'*]. Valters un Rapa, Rīga, 74 pp. [in Latvian].

Easterbrook, D. J. 1999. *Surface Processes and Landforms*. 2nd edn. Prentice-Hall, Upper Saddle River, New Jersey, 546 pp.

Eberhards, G. 1972. *Stroenie i razvitie dolin bassejna reki Daugava* [*Morphology and Development of the Daugava River Basin*]. Zinātne, Riga, 131 pp. [in Russian].

Gustafson, E. J. & Parker, G. R. 1994. Using an index of habitat patch proximity for landscape design. *Landscape and Urban Planning*, **29**, 117–130.

Guzzetti, F., Carrara, A., Cardinali, M. & Reichenbach, P. 1999. Landslide hazard evaluation: a review of current techniques and their application in a multi-scale study, central Italy. *Geomorphology*, **31**, 181–216.

Hutchinson, J. N. 1988. Morphological and geotechnical parameters of landslides in relation to geology and hydrogeology. In *Landslides: Proceeding of the 5th International Symposium on Landslides, Vol. 1* (Bonnard, C., ed.), pp. 10–35. Brukfield: Balkema, Rotterdam.

Jarvis, A., Reuter, H. I., Nelson, A. & Guevara, E. 2008. *Hole-filled SRTM for the Globe Version 4, Available from the CGIAR-CSI SRTM 90m Database*. Available online: http://www.cgiar-csi.org/srtm-90m-digital-elevation-database-v4-1 [accessed 10 Nov. 2011].

Jumiķis, A. R. 1964. *Mechanics of Soils: Fundamentals for Advanced Study*. Van Nostrand, Princeton, 483 pp.

Kalniņa, A. 1995. Climate. In *Latvijas daba 2. sēj.* [*Latvian Nature, 2. Band*] (Kavacs, G., ed.), pp. 247–251. Latvijas Enciklopēdija, Rīga [in Latvian].

Kellerer-Pirklbauer, A., Proske, H. & Strasser, V. 2009. Paraglacial slope adjustment since the end of the Last Glacial Maximum and its long-lasting effects on secondary mass wasting processes: Hauser Kaibling, Austria. *Geomorphology*, **120**, 65–76.

Kohv, M., Talviste, P., Hang, T., Kalm, V. & Rosentau, A. 2009. Slope stability and landslides in proglacial varved clays of western Estonia. *Geomorphology*, **106**, 315–323.

Lee, S., Ryu, J. H., Won, J. S. & Park, H. J. 2004. Determination and application of the weights for landslide susceptibility mapping using an artificial neural network. *Engineering Geology*, **71**, 289–302.

McCarthy, D. F. 2002. *Essentials of Soil Mechanics and Foundations*. 6th edn. Prentice Hall, Upper Saddle River, Columbus, 788 pp.

Panin, A. V., Fuzeina, J. N. & Belyaev, R. V. 2009. Long-term development of Holocene and Pleistocene gullies in the Protva River basin, Central Russia. *Geomorphology*, **108**, 71–91.

Poesen, J., Nachtergaele, J., Verstraeten, G. & Valentin, C. 2003. Gully erosion and environmental change: importance and research needs. *Catena*, **50**, 91–133.

Saltupe, B. 1982. Osobennosti morfologii stroeniya i formirovaniya prolyuviya krupnogo konusa vynosa v drevnej doline reki Gauya [Morphological characteristics and development of the old gully fan in the Gauja River valley]. In *Sovremennye ekzogennye protsessy i metody ikh issledovaniya* [*Contemporary Exogenous Geological Processes and Their Investigation*] (Eberhards, G., ed.), pp. 115–125. Latvian State University Press, Rīga [in Russian].

Schmidt, J. & Dikau, R. 2004. Modeling historical climate variability and slope stability. *Geomorphology*, **60**, 433–447.

Sleinis, I., Ašmanis, K., Delle, N., Siliņš, J. & Lamsters, V. 1933. *Daugava. Sērija 'Jaunais zinātnieks'* [*River Daugava. Series 'New Scientist'*]. Valters un Rapa, Rīga, 107 pp. [in Latvian].

Sobol, I. 1994. *A Primer for the Monte Carlo Method*. CRC Press, Boca Raton, 107 pp.

Soms, J. 2006. Regularities of gully erosion network development and spatial distribution in south-eastern Latvia. *Baltica*, **19**, 72–79.

Takčidi, E. 1999. *Datu bāzes 'Urbumi' dokumentācija* [*Documentation of the Database 'Boreholes'*]. State Geology Survey, Rīga.

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

Van Den Eeckhaut, M. & Hervás, J. 2012. State of the art of national landslide databases in Europe and their potential for assessing landslide susceptibility, hazard and risk. *Geomorphology*, **139–140**, 545–558.

Van Den Eeckhaut, M., Poesen, J., Verstraeten, V., Vanacker, J., Moeyersons, J., Nyssen, J. & van Beek, L. P. H. 2005. The effectiveness of hillshade maps and expert knowledge in mapping old deep-seated landslides. *Geomorphology*, **67**, 351–363.

Van der Linden, P. & Mitchell, J. F. B. 2009. *Climate Change and Its Impacts at Seasonal, Decadal and Centennial Timescales*. Met Office Hadley Centre. Available online: http://ensembles-eu.metoffice.com/docs/Ensembles_final_report_Nov09.pdf [accessed 15 Dec. 2011].

Veinbergs, I. 1975. Formirovanie Abavsko-Slotsenskoj sistemy dolin stoka talykh lednikovykh vod [Formation of the Abava-Slocene system of glacial meltwater drainage valleys]. In *Voprosy chetvertichnoj geologii* [*Problems of Quaternary Geology*] (Danilāns, I., ed.), pp. 82–102. Zinātne, Rīga [in Russian, with English summary].

Venska, V. 1982. Sovremennye geologicheskie protsessy na territorii natsional'nogo parka Gauya [Contemporary geological processes in the Gauja National Park]. In *Sovremennye ekzogennye protsessy i metody ikh issledovaniya* [*Contemporary Exogenous Geological Processes and Their Investigation*] (Eberhards, G., ed.), pp. 139–159. Latvian State University Press, Rīga [in Russian].

Xie, M., Tetsuro, E., Qiu, C., Jia, L. Mowen, X., Esaki, T., Cheng, Q. & Lin, J. 2007. Spatial three-dimensional landslide susceptibility mapping tool and its applications. *Earth Science Frontiers*, **14**, 73–84.

Zelčs, V. & Markots, A. 2004. Deglaciation history of Latvia. In *Quaternary Glaciations – Extent and Chronology, Part I: Europe* (Ehlers, J. & Gibbard, P. L., eds), pp. 225–243. Elsevier B.V., Amsterdam.

Zelčs, V., Markots, A., Nartišs, M. & Saks, T. 2011. Pleistocene glaciations in Latvia. In *Developments in Quaternary Science. Quaternary Glaciations – Extent and Chronology. A Closer Look, Vol. 15* (Ehlers, J. et al., eds), pp. 221–229. Elsevier B.V., Amsterdam.

Maalihked ja erosioonilised nõlvaprotsessid Gauja jõe orus Sigulda ning Līgatne linna vahelisel lõigul

Kārlis Kukemilks ja Tomas Saks

On antud ülevaade praegustest ja varasematest nõlvaprotsessidest Gauja jõe orus. Selleks kaardistasid autorid välitöödel ja kaardimaterjalide alusel Sigulda ning Līgatne vahelisel lõigul esinevad maalihked ja uhtorud. Kokku kaardistati üle 500 erosioonilise vormi ja statistiliste vahenditega tõestati nende koondumine klastritesse. Järgnevalt uuriti korrelatsioonianalüüsi abil nõlvade tundlikkust nimetatud protsessides, vaadeldes uuritud vormide suhteid nõlvade litoloogia, nõlvakalde ja -kuju ning uhtorgude paigutuse vahel. Leitud korrelatsioonikordajate abil ennustati nõlvade tundlikkust erosioonilistele nõlvaprotsessidele. Tulemusi kontrolliti analüüsist välja jäetud kontrollvalimi abil. Maalihete puhul õnnestus kasutatud metoodika abil maalihete ennustamine 16% edukamalt kui juhusliku valiku korral.

Uhtorgude puhul täheldati suuremat esinemissagedust uuringuala põhjaosas, põhjuseks ilmselt erosiooni pidurdavate tugevamate dolomiidikihtide avanemine ala lõunaosas. Autorid rekonstrueerisid endise reljeefi, võttes aluseks erosioonist vähem mõjutatud orulõigud, ja arvutasid välja erosiooniga ära viidud pinnase mahud. Vasakkaldal toimunud intensiivsemat erosiooni seletavad autorid selles küljes asuva Vidzeme kõrgustikul paiknenud jääpaisjärvede mahajooksudega. Ka suuremad uhtorud on autorite arvates kujunenud juba Pleistotseeni lõpul.