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GIS-based alluvial fan analysis: a case study in the Eastern part of the North Alföld Periphery (Hungary)

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Abstract
In this study, we investigate the geomorphological features of the Eastern part of the North Alföld Periphery, focusing on the alluvial fans. Density mapping, aspect, directional statistical analysis, and swath profiling were applied to identify regional spatial patterns and drainage characteristics. Utilizing historical maps, satellite imagery and a digital elevation model, we digitized and analyzed the abandoned riverbeds to understand the landscape's formation, evolution and current state. The western part of the research area is primarily formed by the Tarna River alluvial fan, which exhibits complex development. The middle section, located between Hanyi-ér and Csincse, comprises coalesced alluvial fans of Bükkalja streams, shaped by the blockage from larger fans on the western and eastern edges. The Sajó-Hernád alluvial fan marks the eastern boundary. The erosion of its ancient western branch reduced the extent of the Bükkalja alluvial fan system. This research highlights the need for more detailed studies, including stratigraphy and seismic profile interpretation, to understand better the tectonic and sedimentary processes that have influenced the region's geomorphological evolution.

Keywords
alluvial fan, abandoned riverbeds, swath profile, swath analysis, GIS

Introduction

In our previous research papers (Vágó, 2010, 2012; Pecsmány & Vágó, 2020; Pecsmány, 2020, 2021; Pecsmány et al., 2021a, 2021b, 2022), we examined the development and geomorphological properties of the Bükkalja drainage network by applying diverse GIS-based analytical methods. In this study, we explored the geomorphological features of the Eastern part of the North Alföld Periphery, with a particular focus on the alluvial fans and abandoned riverbeds that characterize this region. These landforms, shaped by centuries of fluvial activity, offer valuable insights into the historical dynamics of water flow and sediment deposition. Our research aimed to analyze the formation, evolution, and current state of these features, contributing to a better understanding of the region's geological history and its ongoing landscape development processes.

Research area

The research area (Fig. 1) is located in the Eastern part of the Észak-alföldi-peremvidék (North Alföld Periphery) region, and it is divided into four micro-regions: the Alsó-Tarna-sík (Lower Tarna Flat), the Hevesi-sík (Heves Flat), the Borsodi-Mezőség (Borsod Flat), and the Sajó-Hernád-sík (Sajó-Hernád Flat) (Csorba et al., 2018).

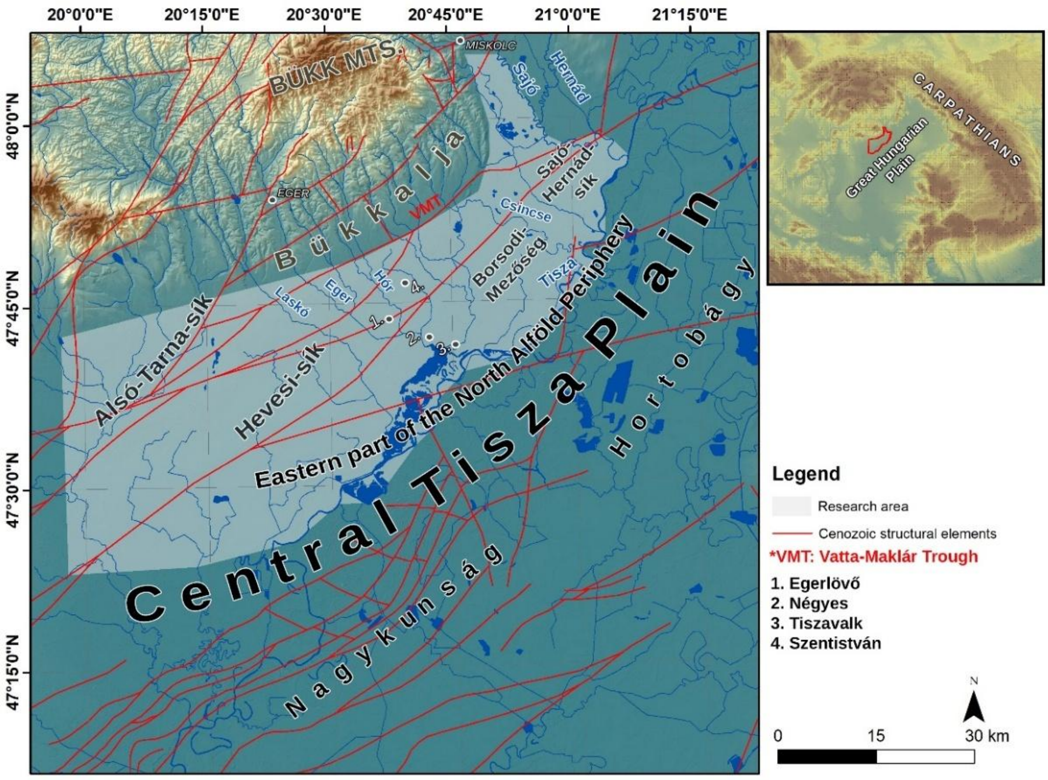

Fig. 1. The location of the research area (Cenozoic structural elements from Haas et al. (2010)).

These micro-regions are difficult to delineate from each other based on their similar morphological characteristics.

All of them were covered by accumulated fluvial sediments of rivers and streams descending from the Északi-középhegység (North Hungarian Range) (Fig. 2). The streams bifurcating on the alluvial fans created secondary alluvial fans (Gábris, 2011a, 2022). As a result of their development, a series of more or less coalesced alluvial fans formed (Mezősi, 2017). Due to the sequential climatic and tectonic processes during the Quaternary period, the deposition of sediment and subsequent incision into the already-formed alluvial fan occurred intermittently (Gábris, 2022). The surface of alluvial fans, which dried up due to the incision of the rivers and main streams, was further shaped by the wind and human activity (Nagy, 2002; Mezősi, 2011).

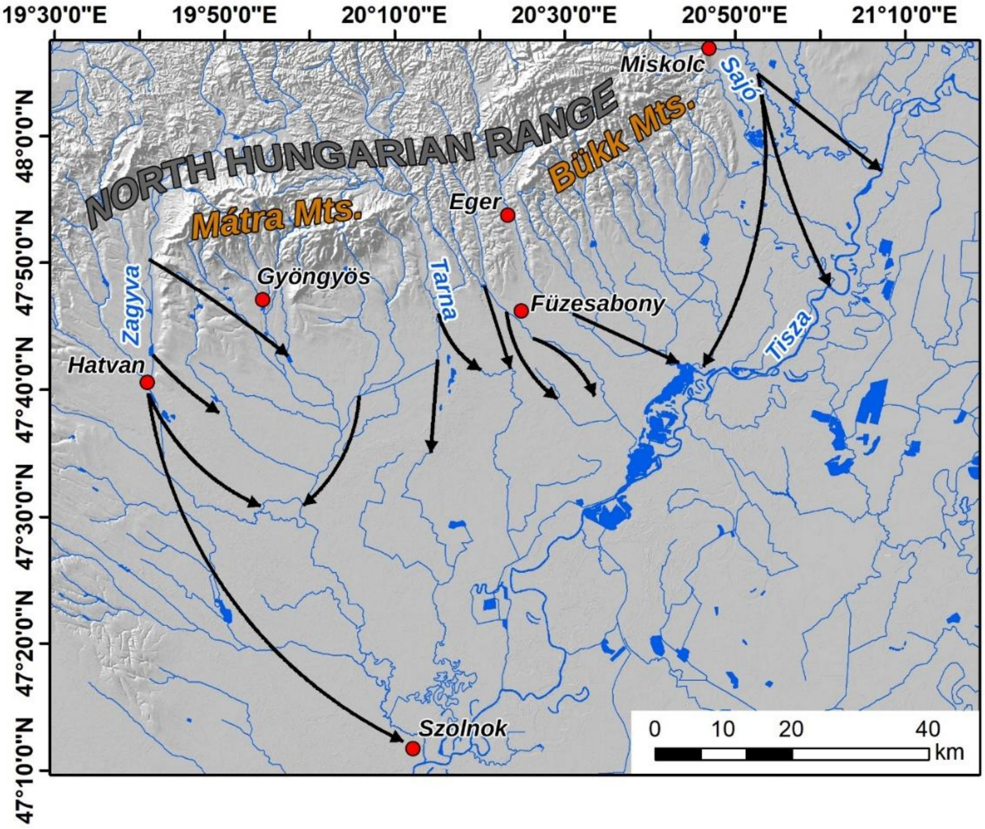

Fig. 2. Direction of ancient streams based on Lovász (2006).

The tributaries of the Tarna and Zagyva streams formed an extensive alluvial fan (Alsó-Tarna-sík) in the southern foreland of the Mátra Mountains, which underwent significant transformation during the Quarternary period due to tectonic movements (Gábris, 2011). According to Gábris (2011) research, only remnants of the alluvial fan are now identifiable on the surface.

The Hevesi-sík was formed by the Laskó and Eger stream systems (Gábris, 2011a, 2022). Some theories suggest that the Tarna river may have also played a role in shaping the landscape (Székely, 1969), although there is no geological or morphological evidence to confirm this (Gábris, 2011b, 2022). The area is considered tectonically active, as confirmed by previous structural geology studies (Petrik, 2016; Pecsmány, 2020, 2021). The subsidence of the Hevesi-sík during the Holocene is indicated by the Holocene cover deposited over Pleistocene sediments, with low loess and sand ridges found only in the area between the Laskó and Eger streams (Gábris, 2011a, 2022).

According to some assumptions, the development of the alluvial fan built by the Zagyva-Tarna and Eger-Laskó rivers was influenced by the subsidence of the Jászság Basin. As a result of the subsidence of this basin, the streams filled the area towards SSE, SSW direction (Székely, 1969; Lovász, 2006; Gábris, 2012).

The Borsodi-Mezőség was formed by streams descending from the Bükk Mountains, mostly by the Hór and Csincse streams. The Csincse stream may have carried a significant amount of water even during the Middle Ages, according to historical sources describing the Battle of Mezőkeresztes (1526) (Tóth, 2000). Based on abandoned riverbeds, Pinczés (1978) identified a former hydrographic centre around Szentistván in the Borsodi-Mezőség, suggesting that the direction of the Hór and Tardi streams was determined by a local depression. Structural geological and geophysical studies have identified several ~NE-SW oriented structures south of the Vatta-Maklár Trough, beyond the Mezőkövesd and Mezőkeresztes Ridges (Petrik, 2016, Kiss, 2005a, 2005b), whose neotectonic activity cannot be dismissed (Pecsmány, 2020, 2021). This suggests that the geomorphological activity of the streams was also influenced by structural geological conditions.

The eastern third of the research area encompasses the Sajó-Hernád alluvial fan (Gábris and Nagy, 2005). Based on Franyó's (1966) research, the centre of the alluvial fan is located around Miskolc, extending about 35-40 km to the South toward the Tisza River (Gábris and Nagy, 2005; Gábris, 2022). According to Gábris (1970) and Nagy (2002), the alluvial fan can be divided into four parts: an older surface with braided channels and three increasingly younger surfaces with differently sized abandoned riverbeds.

Materials and Methods

Materials

For the digitization of abandoned riverbeds, we used historical maps (First and Second Military Surveys) (Hofstätter, 1989; Jankó, 2001; Timár, 2004; Timár et al., 2006; Molnár & Timár, 2009) and topographic maps (EOTR map sheets), as well as manuscript archival maps that we georeferenced (Fig. 3). The abandoned riverbeds were digitized from these cartographic sources, Google Earth satellite imagery and a 25-meter spatial resolution digital elevation model (HydroDEM). The cross-sectional analysis, as well as the morphometric and statistical examinations of the terrain model, were conducted using the HydroDEM.

Fig. 3. The georeferenced pre-regulation map of the "Füzes-Abony area, including the Szikszó and Kisbuda farms", along with the abandoned riverbeds identified both on the satellite imagery and the archive maps (Source: Heves County Archives, Economic Archives of the Archdiocese of Eger, Manuscript Maps of Heves County).

Based on Borehole Data Annuals published by the Institute of Hungarian Geological Survey (1970-1988), we developed a comprehensive borehole database, which includes the stratigraphic sequences encountered during drilling and the thickness of each layer. We constructed a thickness map of the Quaternary sediment deposits within the study area using this data. Additionally, we produced a Pre-Neogene basement map.

Swath Profiling

In geomorphological research, cross-sectional analysis has been applied for decades, as it allows us to understand the characteristic landforms of a given research area (Telbisz et al., 2011, 2012, 2013). Cross-sectional analysis has previously been successfully applied in examining alluvial fan areas, with particular emphasis on determining their slope conditions (Sümeghy et al., 2013; Sümeghy, 2014). However, this method is quite subjective, depending heavily on the researcher, and the cross-sections' orientation must often be fit to additional data sources (for instance, the path of a 2D seismic data section). As a result of this subjective profile orientation, local minimum and maximum locations may be omitted/included from the analysis, which may cause false results. To overcome this problem, swath analysis is used, which is not based on a single cross-section path but rather along a defined swath, making it statistically more reliable (Telbisz et al., 2012, 2013; Pecsmány et al., 2021b).

The essence of the method is that evenly spaced cross-sections are created along a predetermined rectangular area, and the minimum, maximum, average, and quantile values of the elevation data (pixel values) within these cross-sections are determined. These values are then plotted on a diagram using uniform spacing (Telbisz et al., 2011, 2012, 2013; Kovács, 2013; Pecsmány et al., 2021b). Additionally, the values calculated along the cross-sections can also be displayed on a map. Furthermore, the method allows for a more comprehensive analysis of terrain variations, providing a clearer understanding of geomorphological patterns across the study area (Fig. 4).

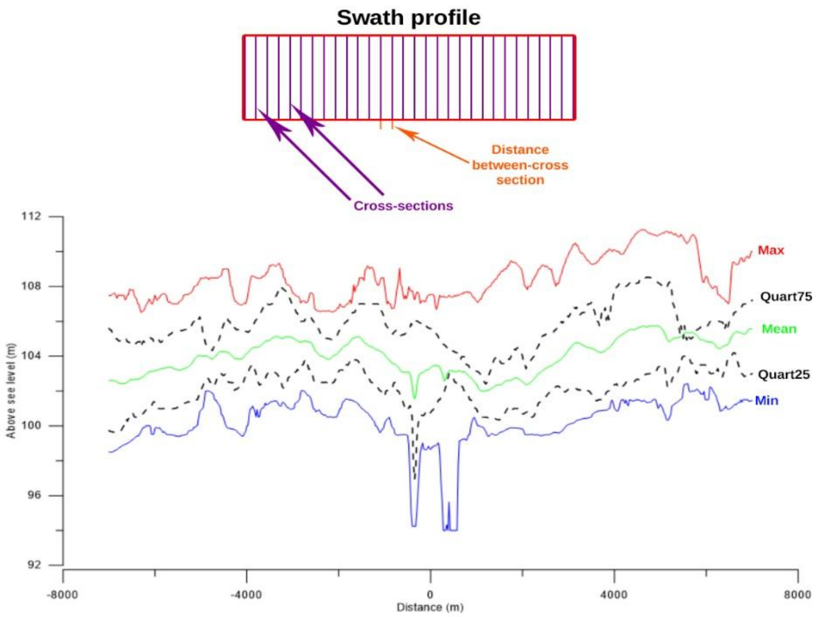

Fig. 4. Swath analysis method.

In our study, we created multiple swath profiles next to each other to cover the entire research area. Each swath profile has a length of 60 km and a width of 3 km. In the E-W direction, we applied 20 profiles, while in the SW-NE direction, perpendicularly arranged to the general aspect of the Bükkalja area, we placed 15 profiles. Based on the DEM, we also examined the mean and maximum elevations a.s.l.

Analysis of abandoned riverbeds

For the directional statistical analyses, we utilized the 'Creating Rose Diagrams from Endpoint Data' tool in RockWorks 16 software. We analyzed the direction of the abandoned riverbed sections based on their total length. The directional length frequency of the abandoned riverbeds was illustrated in rose diagrams with 10-degree class intervals, expressed as a percentage (Pecsmány et al., 2021a, 2022). Due to the meandering of these digitized riverbeds, it is difficult to determine their main direction. Therefore, we generalized the riverbeds by replacing them with straight 1 km segments and determined the direction of these segments. The density map of the abandoned riverbeds was created using the 'Kernel Density' tool built into ArcGIS Pro. We also analyzed the slopes using the ArcGIS Pro tool. In order to analyze the directions of slopes in the area on a larger scale and to distinguish larger features, we created DEMs with various pixel sizes (1x1 km, 2x2 km, 3x3 km, 4x4 km, and 5x5 km), which were then used for deriving aspect rasters with these resolutions. Subsequently, we standardized the geometric resolution of these aspect datasets. The standardized aspect rasters were then used in the "Cell Statistics" module. We calculated the "Majority," which provided the most frequent aspect for each pixel. This approach allowed us to determine which aspect type was most commonly observed for a given location in the grid.

Results

Analyzing the direction of the slopes, it can be seen that in the lower-lying Southern surroundings, there is no dominant aspect, while in the area of the abandoned riverbeds, the aspect is more uniform, having large areas with the same aspect (Fig. 5). These areas are the gently sloping sides of the abovementioned alluvial fans. The streams of the research area, running towards the Central Tisza Plain (Figure 1), built these alluvial deposits, each of their eastern sides are facing towards SW direction, while their western sides are facing towards S, SE direction (Fig. 5). Based on the spatial pattern identified aspect maps (Figure 5), the area can be divided into three geomorphological units.

The results of the swath profile analysis can be seen in Figure 6. We created 10 profiles directly next to each other to get an overview of the elevation differences. In the middle section of the swath series, 3 areas can be identified with relatively higher elevation a.s.l. Therefore, we analyzed profiles Nr. 4-6. in details. The area with the highest elevation between the Western boundary of the research area and the Hanyi-ér is the alluvial fan of the Tarna river. Between Hanyi-ér and Csincse – the latter is the lowest-lying part of our area – the undulating curves of the profiles indicate the location of the Bükkalja foreland, where the individual alluvial fans of the streams cannot be delineated. East of Csincse stream, the Sajó-Hernád alluvial fan can be identified.

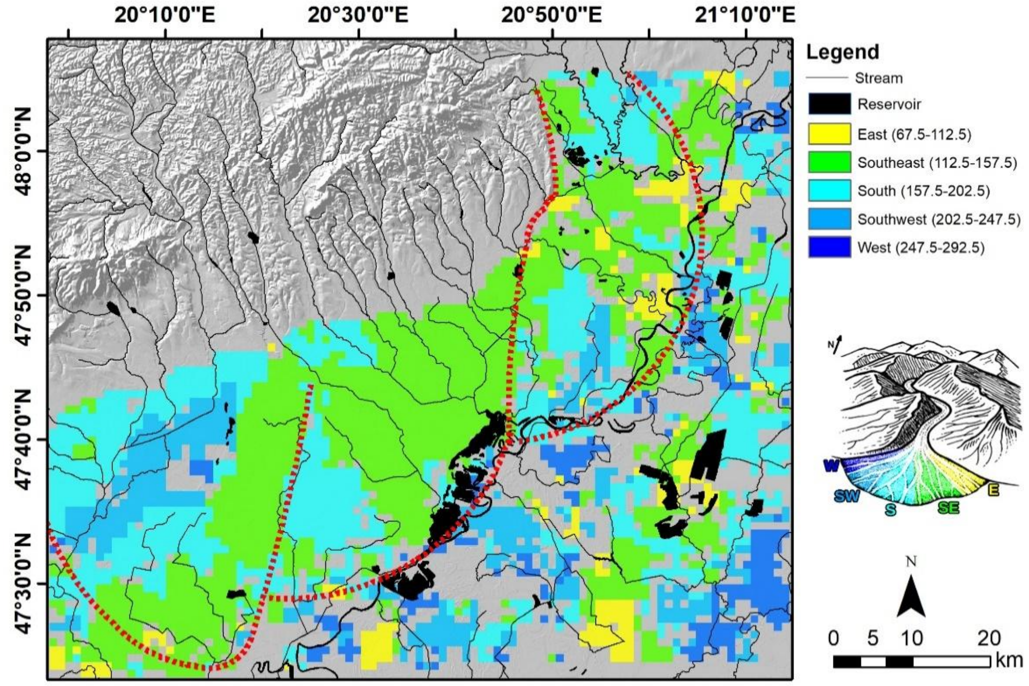

Fig. 5. The majority of the data sets for the research area and the illustration of alluvial fans (illustration based on the Merriam-Webster dictionary).

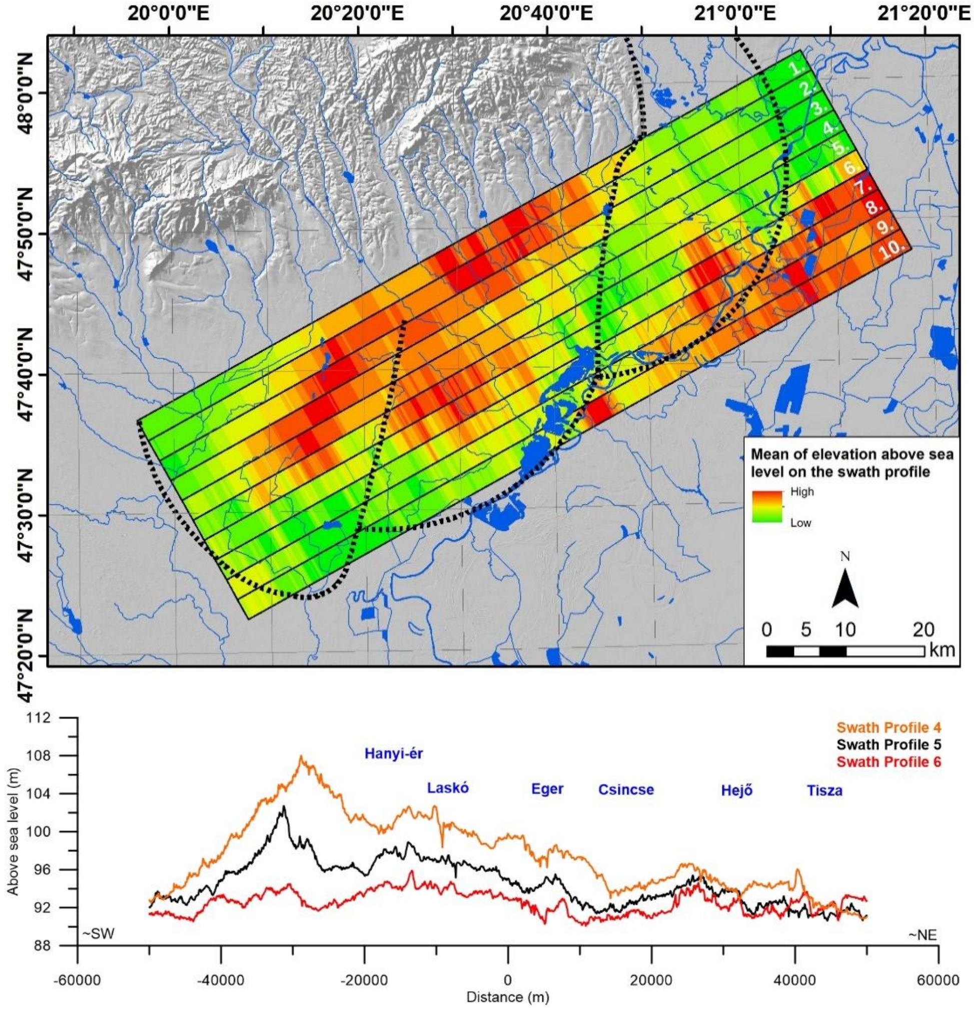

Fig. 6. Swath analysis in the research area.

In order to try to delineate individual fans in the Bükkalja foreland, we analyzed the density and direction statistical characteristics of the ancient drainage network using the digitized abandoned riverbeds.
The results of the Kernel density mapping are visualized in Figure 7, providing a comprehensive overview of the spatial distribution of abandoned riverbeds within the study area. Upon analyzing the density of these landforms, five distinct spatial groups emerge (W-E order):

- Group 1, between Laskó and Eger streams (Hevesi-sík and Western part of Borsodi-Mezőség, max density 1.5 km/km^2).
- Group 2, between Eger and Hór streams (max density 2.3 km/km^2)
- Group 3, between Hór and Sályi streams (max density 1.8 km/km^2)
- Group 4, between Sályi and Hejő streams (max density 2.3 km/km^2)
- Group 5 is the Easternmost group with the highest density values (max density 3.2 km/km^2).

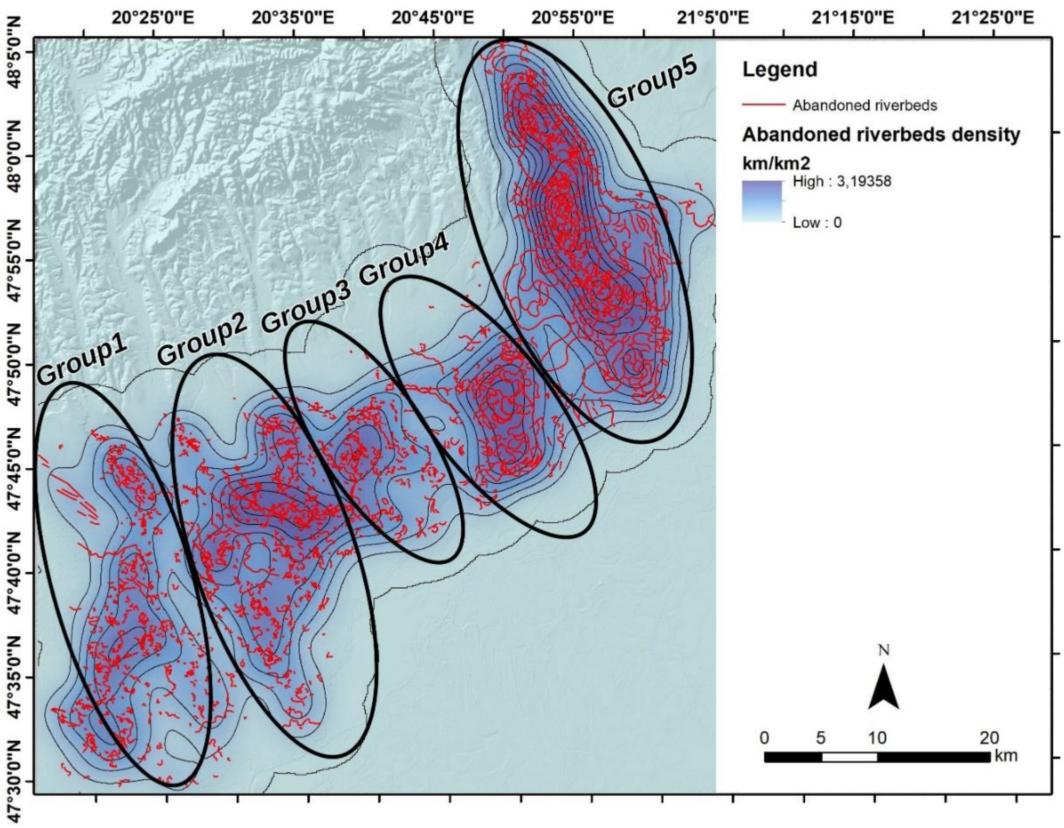

Fig. 7. Abandoned riverbeds density of the research area.

The results of the directional statistical analysis of these 5 groups can be seen in Figure 8. It can be stated that in the case of groups No. 1-3, the mean direction is NW-SE. However, there are small differences in the dominant direction: while groups 1-2 have NW-SE, Group 3 can be characterized by N-S dominant direction. Group 4 has the most distinct properties; this group demonstrates a more dispersed directional pattern, lacking a clear dominant axis but showing some preference for N-S. In the case of Group 5, the mean direction is NNW-SSE, while – similarly to Group 4 – there is no clear dominant direction. It suggests that these groups belong to the same alluvial landform.

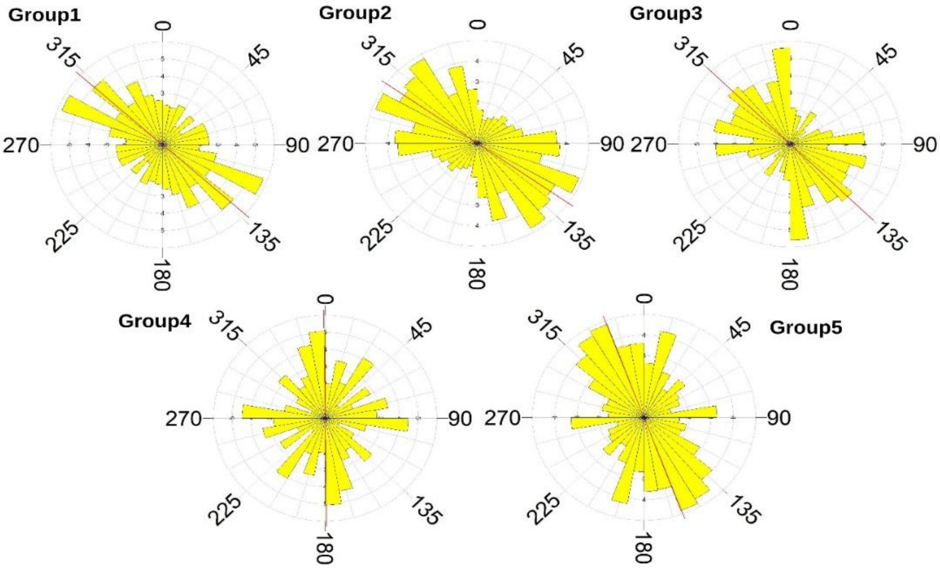

Fig. 8. Direction statistics for groups by density map abandoned riverbeds and aspect of research.

The northern boundary of the alluvial fan coincides with the Vatta-Maklár Fault (VMF). North of this, we identified only the remnants of the lowest terrace (Fig. 9, A) (Pecsmány, 2016, 2017). Between the Laskó and Eger streams, the boundary of the alluvial fan can be identified further south (Fig. 9, B). This area is still subsiding, as evidenced by the incision of the watercourse (Pecsmány, 2017, 2021), forming meander terraces along the Laskó and Eger streams (Pecsmány, 2016, 2017, 2021). Based on this, the formation of the lowest terrace along the two watercourses can be attributed to structural causes.

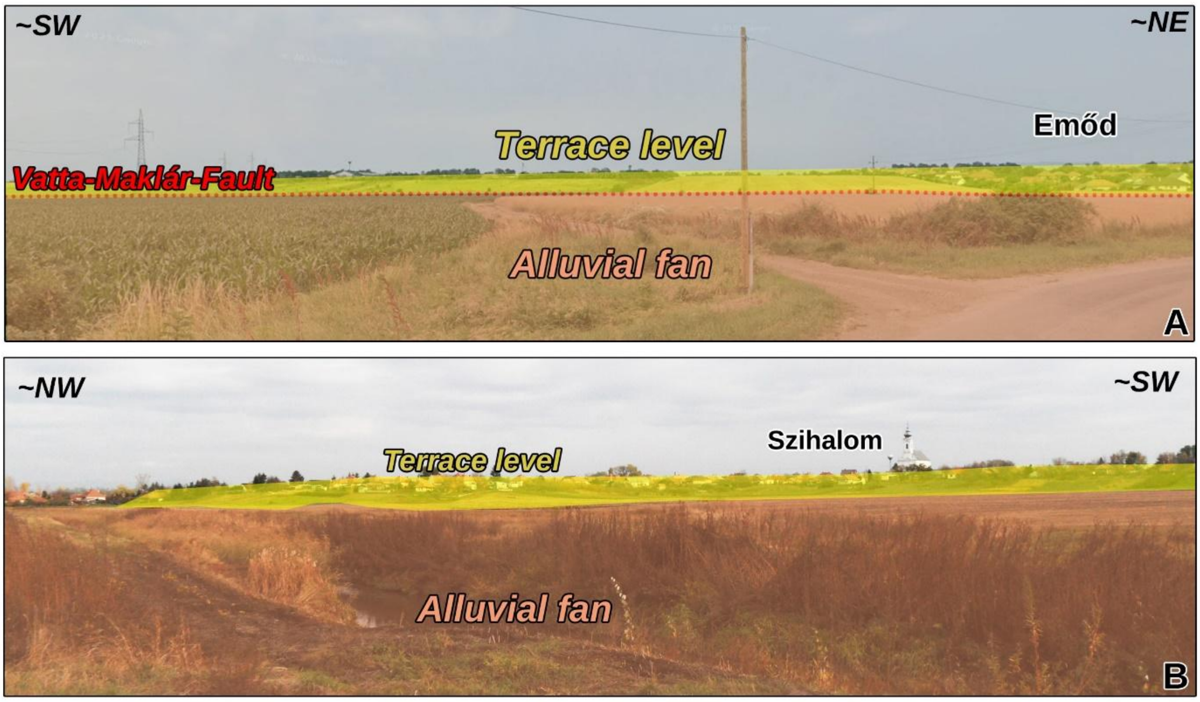

Fig. 9. Alluvial fan and lower terrace level in the eastern (A) and western (B) part of the research area.

South of Kál, the Tarna changes its direction. In this area, several faults converge with each other (Vatta-Maklár Fault, Tárkány Fault, Berva Fault) (Haas et al., 2010; Gál et al., 2024), which were active during the Quaternary period with different kinematics (Petrik, 2016; Pecsmány, 2020, 2021). The change in direction was likely caused by the footwall block of the fault, halting the southeastward growth of the alluvial fan and initiating its degradation. The degradation was caused by the incision of streams formed due to the subsidence of the Jászság Basin (JB), as well as by deflation processes.

The direction of the watercourses originating from the Bükk Mountains and the development of the merged Bükkalja alluvial fan were regionally influenced by the uplift of the Bükk and the varying degrees of subsidence of the sub-basins in the Jászság Basin. Based on the thickness map of Quaternary sediments, the watercourses seem to be directed toward a subsidence zone near Négyes (assumed sub-basin of the Jászság Basin). Additionally, another sediment trap can be identified between the Hanyi-ér and Eger streams (Fig. 10), which is still subsiding (Pecsmány 2016, 2017, 2021).

The development of the Sajó-Hernád alluvial fan was also influenced by the varying degrees of subsidence of the sub-basins in the Jászság Basin. According to Gábris and Nagy (2005) and Gábris et al. (2012), the eastern channel generations are considered to be the oldest branches. Based on this, at the end of the Pleistocene (Late Pleniglacial – 28-13 ka), the Sajó likely flowed toward the subsidence zone near Négyes, eroding the alluvial fan built by the watercourses descending from the Bükk foothills. The river settled into its current position due to the partial filling of the sedimentary trap near Négyes and/or the faster subsidence of the Sajó-Hernád Depression and the Polgár Graben. Both subsidence zones can be distinguished on the Pre-Neogene basement map and the Quaternary sediment thickness map (Fig. 10).

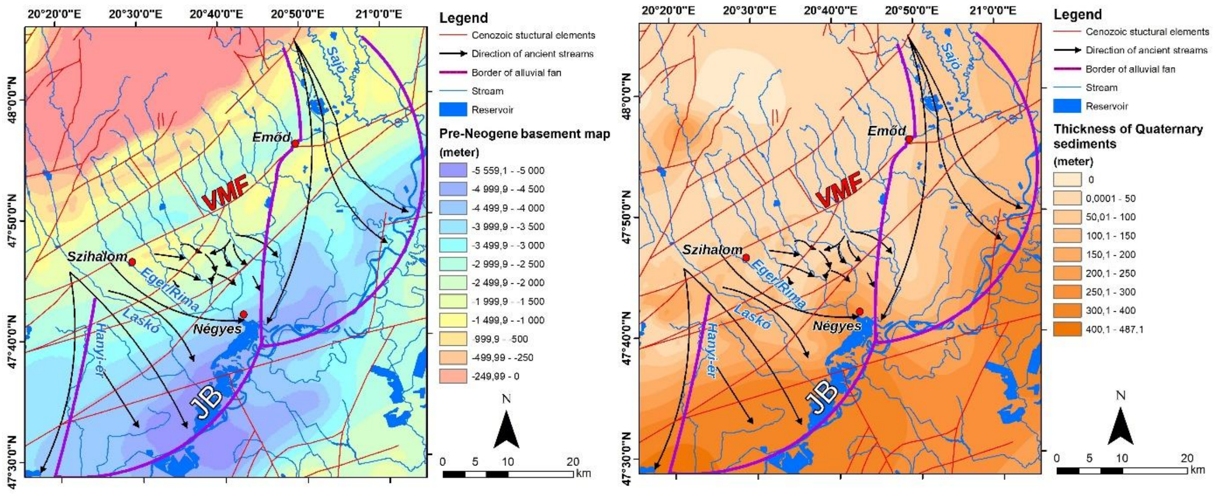

Fig. 10. Pre-Neogene basement map and Thickness of Quaternary sediment of the research area (Cenozoic structural elements from Haas et al. 2010).

Conclusion

Based on the aspect, directional statistical analysis, and swath profile data, the research area can be classified into three distinct spatial groups of alluvial fans, each characterized by unique geomorphological and directional properties.

Western Boundary – Tarna River Alluvial Fan

It can be stated that the western boundary of the area – in line with the literature – is built up mostly by the alluvial fans of the Tarna river (according to Székely (1969)). The fact that this is the highest part of the entire area and the aspect of its vicinity suggests that this fan has a complex development, which requires further investigations. Tarna changes direction due to the convergence of several Quaternary-active faults (Vatta-Maklár, Tárkány, Berva), with the footwall block likely causing the shift, halting the southeastward growth of the alluvial fan and triggering its degradation.

Middle Section – Coalesced Fans of Bükkalja Streams

The middle part, between Hanyi-ér and Csincse, is built by the alluvial fan system of the Bükkalja streams. It is evident, and clearly visible on the swath profiles (Fig. 6), that this individual part was built up by alluvial deposits. However, these landforms cannot be delineated by applying GIS-based geomorphometric methods (Fig. 10). However, based on the analysis of abandoned meanders, it can also be concluded that the ancient streams arriving in the central part of the study area were blocked by the larger alluvial fans (Eger-Laskó, Sajó-Hernád) located on the western and eastern edges, which resulted the development of the coalesced alluvial fans. This embankment influenced the formation of the small lakes that are depicted on the 18th -19th century Cadastral and Historical Military Surveys. The development of this section was shaped by the uplift of the Bükk and the subsidence of the Jászság Basin sub-basins.

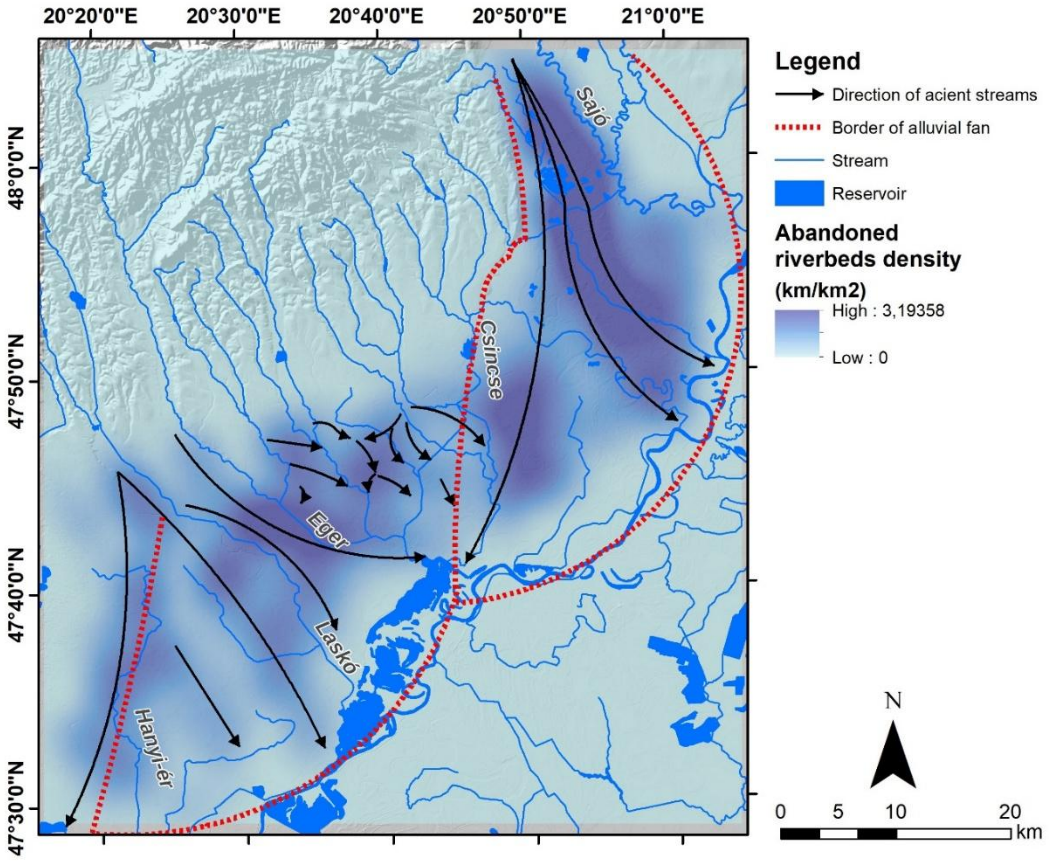

Fig. 10. Direction of ancient streams and border of alluvial fans.

Eastern Boundary – Sajó-Hernád Alluvial Fan

The Eastern boundary of the area is the Sajó-Hernád alluvial fan, together with the recent catchment of Csincse (according to Nagy (2002)). The abandoned riverbeds of the latter stream exhibit distinct characteristics, including a predominantly southern aspect and a dominant NE-SW orientation. These features, along with their relatively lower elevation above sea level, align closely with the topographic and geomorphological characteristics of the Sajó-Hernád alluvial fan. This result also highlights that the spatial extent of the Bükkalja alluvial fan system might have been reduced since this branch might have eroded the eastern part of the formerly deposited sediments.

This study resulted in a preliminary delineation of alluvial fans within the research area, identifying distinct spatial and geomorphological groups. However, further detailed studies, including fieldwork, stratigraphy, and more advanced geomorphometric analyses, are essential for a more comprehensive understanding of the evolutionary history of these landforms. We also intend to interpret the available 2D seismic profiles, which will provide us with valuable information about the subsurface structures and fault systems that may have driven the surface deformations. By combining borehole data with seismic interpretations, we aim to reconstruct the tectonic and depositional history of the region in greater detail. These additional research methods are expected to yield new insights into the surface evolution of the region, enhancing our understanding of how tectonic forces have shaped the formation of alluvial fan systems and other geomorphological features.

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