The study area is situated between 16° – 17° E and 47° – 47.5° N. The differential vertical motion implies neotectonic activity and some associated geomorphologic features (e.g. wind gaps, small streams in large valleys, etc.) may be observed as a result of drainage reorganization. After ~8.7 Ma the area was characterized by a wide alluvial plain and a marsh zone. Later on, rivers spread their gravelly sediment over the whole area, creating gravel terraces in the west and an almost continuous gravel cover in the eastern, planar terrain. The drainage network in the hilly region is oriented to the NW–SE alluviation direction, but each river has several abrupt turns in its lower course.

In order to identify wide and planar features some DEM-derived markers were used. First, two parameters were considered for each pixel: slope angle and relative height. Second, two parameters were used to classify wind gaps: incision of the valley bottom and relative elevation. In our case, the less uplifted, but more deeply incised valleys are the most obvious markers of drainage reorganization. Using the mentioned methods, terraced valleys, wide alluvial valleys and deeply incised valleys, as well as wind gaps, are recognizable and help interpretation of former river connections.

The spatial pattern of the identified wind gaps suggests that drainage reorganization was significantly influenced by north-facing escarpments. Therefore, the map provides additional information to the scientific debate concerning the post-Miocene tectonic activity of the Eastern Alpine Foreland.

Keywords: Eastern Alpine Foothills; drainage reorganization; Pleistocene; geomorphometry; DEM; GIS

1. Introduction

The study area is situated between 16° – 17° E and 47° – 47.5° N, between the still uplifting Eastern Alps (Grundmann and Morteani, 1985; Wagner et al., 2010) and the subsiding Little Hungarian Plain (e.g. Joó 1992). The transitional situation between realms of different vertical motion
implies neotectonic activity and associated geomorphologic features may be observed such as drainage reorganization forced by up warping zones and faults.

The Pannonian Lake, which filled the whole basin between the Alps, the Carpathians and the Dinarides during the second part of the Miocene was later filled by rivers transporting high amount of sediment from the uplifted Eastern Alps. After the lacustrine environment had changed, the study area was characterized by a wide alluvial plain and marsh zone. An initial NW–SE direction of the alluviation was determined by Magyar, Geary, and Müller (1999), whilst Kosi, Sachsenhofer, and Schreilechner (2003) used high-resolution seismic data to observe a buried river channel showing the same NW–SE direction. During the Pleistocene high amounts of gravel covered the area, accumulated by rivers which often changed their direction (Szádeczky-Kardoss, 1941; Ádám, 1962). The present drainage network in the hilly region is generally oriented according to that direction, but each river has several abrupt turns in their lower course. In some cases, only 1 turn (e.g. Gyöngyös, Lapincs/Lafnitz rivers), but other rivers may have up to six turns (e.g. Strem, Répce/Rabnitz rivers).

At present, the study area can be divided into several parts taking into consideration the general morphology. The south-eastern part of the area is totally plain, mostly covered by Pleistocene gravel deposited by various paleorivers. The western area is more dissected, mainly by the wide NW–SE valleys of Pinka and Strem, but also by the highly incised N–S valleys (e.g. Dürrer Bach, Lukabach Limbach, Hoppachbach). Note, that extended river terraces belong to the wide valley of the Strem river, which has, at present, negligible discharge. The terraces between the Lafnitz and Strem rivers are gradually younger from west to east, but in the area north of the lower Strem the old to young direction is N–S (Figure 1). The NW–SE streams flow in asymmetric valleys with steep scarps on their southern side, but in some cases relatively significant valleys without streams cross these scarps. These forms are identified as wind gaps, i.e. former passes of paleorivers.

In our previous study, the geometry of buried lignite layers at one of these scarps (near Torony) was evaluated (Kovács and Telbisz, 2013). Horizontal layers are tilted and faulted suggesting that subsurface layers were deformed during (and presumably after) sedimentation and so the area is neotectonically active.

Differences between the former and present drainage network, wide alluvial valleys containing negligible streams, systematic changes in terrace ages, wind gaps, and the deformed lignite layers altogether demonstrate the reorganization of drainage network after the filling up of Lake Pannonian. Abandoned parts of the former drainage network could be analysed through widespread field observations and measurements. In order to locate crucial sites for local investigation, a priori quantitative analysis of terrain data is needed. Using the map presented here, we aimed at the visualization, identification and quantitative analysis of landforms like wind gaps, major incised and alluvial valleys, river terraces and alluvial plains. Taking into consideration traces of abandoned stream sections, former flow directions can be outlined.

2. Methods

Former flow directions are reconstructed in several steps. First, valleys possibly abandoned by former main rivers (i.e. wide alluvial valleys with terrace remnants) are identified. Second, incised but still wide valleys are extracted. If two of them seem to follow each other, the separating drainage divide must be inspected to search for a possible wind gap between them.

In order to identify wide and plain features such as alluvial plains, alluvial valleys, terraces and major incised valleys, some digital elevation model (DEM)-derived parameters were used. NASA SRTM 3″ data (http://www2.jpl.nasa.gov/srtm/) were used for the calculation, using the Hungarian National Grid (EOV) projection. Pixel size was reduced to 65 m, which is
the shorter side of the original $3'' \times 3''$ pixel. Two main parameters were considered during the process: slope angle and relative height of the given pixel. The latter was calculated from the 1 km neighbourhood as the difference between the given pixel elevation and the mean of the neighbourhood. In our case the class types used are shown in Figure 2 and highlighted on the Main Map. The applied window size has to be adjusted to the studied landscape scale. In
our case, it was determined to be smaller than the typical width of alluvial valley floors, but larger than the typical interridge distances in the more dissected parts.

Wind gaps are abandoned valley sections created by streams formerly flowing across the scarp. Continuation of valley segments in the upper reaches becomes abandoned due to river piracy or tectonic uplift of the scarp. However, not only abandoned valleys may dissect a relatively uplifted ridge but other forms of erosion, too. Therefore quantitative investigation is needed to determine if the valley is a wind gap or not. Ridgelines of the scarps were automatically highlighted using the following equation: $H - H_m$, where $H$ is the elevation of the scarp and $H_m$ is the mean elevation of 500 m radius. Thereafter, ridgelines were manually digitized as polylines, and long profiles were extracted along them using ArcGIS 3D Analyst. Local minima were automatically designated as possible wind gaps. In our study, two classifying parameters were used to decide if these are really wind gaps or not. First, incision of the valley bottom (i.e. valley depth relative to the local maximum) and second, relative elevation (height of the valley bottom relative to the foreland height; Figure 3). Parameters were calculated using the following equations: \((H_{2a} + H_{2b})/2 - H_1\) and \(H_1 - H_3\), respectively (Figure 3), where $H_1$ is the elevation of the highest point of the abandoned valley bottom, $H_{2a}$ and $H_{2b}$ are the elevations of the shoulders of the abandoned valley along the scarp and $H_3$ is the elevation of the lowest point in the foreland valley where stream piracy occurred. Colour and size of the circle symbols show incision and relative elevation, respectively. Note that the results are influenced by the subsequent sedimentation and erosion of local maxima. In our case, the less elevated (max. 40 m) but more deeply incised (min. 20 m) forms situated between subsequent valley sections are considered wind gaps. These are the most obvious markers of recent drainage reorganization, therefore larger and lighter circles are connected to these points.

Figure 2. Parameterization of DEM pixels. $Z$ – elevation, $Z_m$ – mean elevation of 1 km neighbourhood (circle radius).

Figure 3. Calculated and represented parameters of possible wind gaps. $H_1$ – elevation of the highest point of the abandoned valley bottom; $H_{2a}$–$b$ – elevation of shoulders of the abandoned valley along the scarp; $H_3$ – elevation of the lowest point in the foreland valley where stream piracy took place.
3. Limitations and applicability

Geomorphometry is a widely useable approach in geosciences, but the applied methods and parameters have to be chosen carefully taking into consideration the geological settings of the study area, the landscape scale, the available DEMs (resolution and generation method) and the aim of the study. According to Ludwig and Schneider (2006) higher slope values (45–60°) are more accurate when using higher resolution DEMs. In addition SRTM is a surface model, therefore the tops of forests are presented instead of solid terrain. Forests can be detected on the map as more rugged surfaces than their neighbouring terrain and bordered by irregular narrow scarps. Applied slope categories were chosen by examining the frequency distribution of slope angles. Values less than 0.55° are dominant in the flat easternmost area, while 0.55–1.37° are typical in the central-eastern parts where the plain surface is slightly tilted. Values of 1.37–2.29° mark relatively high slope values in the hilly area, but these categories are present in the area of the above mentioned tilted plain surfaces and at the narrow scarps between young terraces (yT in the map).

Homogeneity of the Main Map can be improved by applying a smoothing method for the terrain. However, keeping original elevation and slope values was an important constraint in our case, because the use of mean or mode filters for elevation or slope would also remove important features such as narrow marginal scarps of young terraces.

4. Results

Finally, fluvial terraces, wide alluvial valleys and deeply incised valleys have been highlighted along with possible wind gaps between former river segments (orange dotted arrows, see Main Map). These locations are considered wind gaps and were chosen for further detailed field investigations. Terrace width and valley width of the Strem stream and wind gaps also support drainage reorganization. The northern part of the alluvial plains then becomes a planar but tilted surface. Young terraces along southward flowing rivers and narrow scarps between flat units are important results of the chosen representation and can be targets of future field surveys.

The distribution of landforms mainly depends on surface development of the study area. Alluvial plains occur in the eastern area, where parts of the Little Hungarian Plain are subsiding. Former flow directions in that area could only be determined by using local geological investigations, where Szádeczky-Kardoss (1941) and Ádám (1962) demonstrated the NW–SE flow of the Pinka, Gyöngyös and Répce rivers. The middle part of the study area is dissected by E–W scarps, which divide into several segments the formerly continuous N–S valleys. Wind gaps are situated along these scarps between the subsequent valley segments, thus former flow directions can be determined (orange dotted arrow, see Main Map). These scars are found at the northern boundaries of tilted blocks (characterized by higher dominant slope values). At the western boundaries of these N–S-directed tilted blocks, wide alluvial valleys with young terraces are found.

The western part is totally different from the previously described units. Alluvial plains are missing, instead wide alluvial valleys and terrace surfaces are present. The average elevation is much (~50–100 m) higher than in the eastern area, therefore due to the same erosion base level, this part is more dissected by N–S streams. Dividing scarps are frequent, therefore possible wind gaps are also more abundant than in the eastern area. However, plenty are not considered as real wind gaps due to their parameters (high relative elevation and low relative incision) and the lack of subsequent valley segments on opposite sides.

5. Conclusions

Our Main Map emphasizes the local differences in the general morphology of the study area. The south-eastern area is totally flat preserving the original shape of the former alluvial plain.
Northward, the slope is slightly steeper, presumably due to young tectonic deformations and/or due to the pediment style of the area. The applied morphological parameterization highlighted possible abandoned river segments as well as possible wind gaps using quantitative properties that proved to be a successful combination. In the western, more dissected part, several feasible former flow directions could be determined. This could help to outline drainage reorganization stages. Naturally, a reliable demonstration of the existence of abandoned flow directions requires local field measurements and/or geological observations. Our methodology is also suitable to designate locations for field investigations to detect for instance possible tectonic origin of the scarps and determine the age of terraces etc.

**Software**

All data processing and map design were performed using Esri ArcGIS10.

**Acknowledgement**

Our research of Neogene tectonics and tectonic geomorphology of the western Hungarian Alpine foreland was supported by Hungarian Scientific Research Fund (OTKA NK83400, SourceSink Hungary). The scientific activity of Gábor Kovács was partly sponsored by TAMOP 4.2.2 project, Tamás Telbisz was sponsored by Bolyai Scholarship of the Hungarian Academy of Sciences. The present research is realized in the frames of TAMOP 4.2.4.A/2-11-1-2012-0001 high priority ‘National Excellence Program – Elaborating and Operating an Inland Student and Researcher Personal Support System convergence program’ project’s scholarship support, using Hungarian state and European Union funds and co-finances from the European Social Fund.

**References**

Ádám, L. (1962). Gravel cover beyond Rába River [A Rábántúli kavicstakaró]. In Ádám, L., Góczán, L., Marosi, S., Somogyi, S., & Szilárd, J. (Eds.) Néhány dunántúli geomorfológiai körzet jelelmzése. *Földrajzi Értesítő, 11*, 41–52.

Grundmann, G., & Morteani, G. (1985). The young uplift and thermal history of the central Eastern Alps (Austria/Italy), evidence from apatite fission track ages. *Jahrbuch der Geologischen Bundesanstalt, 128*(2), 197–216.

Joó, I. (1992). Recent vertical surface movements in the Carpathian Basin. *Tectonophysics, 202*, 129–134.

Kosi, W., Sachsenhofer, R. F., & Schreilechner, M. (2003). High resolution sequence stratigraphy of Upper Sarmatian and Lower Pannonian Units in the Styrian Basin, Austria. In Piller, W. E. (Ed.): *Stratigraphia Austriaca. – Österr. Akad. Wiss., Schriftenr. Erdwiss. Komm. 16, 63–86*.

Kovács, G., & Telbisz, T. (2013). The role of tectonic and fluvial forces in the formation of the hilly area between Kőszeg Mountains and Rába River [Tektonikus és fluviális hatások a Kőszegi-hegység és a Rába közti dombvidék kialakulásában]. *Földtani Közlöny, 143*, 157–176. (in Hungarian with English abstract).

Ludwig, R. & Schneider, P. (2006). Validation of digital elevation models from SRTM X-SAR for applications in hydrologic modelling. *ISPRS Journal of Photogrammetry & Remote Sensing, 60*, 339–358.

Magyar, I., Geary, D. H., & Müller, P. (1999). Paleogeographic evolution of the Late Miocene Lake Pannon in Central Europe. *Palaeogeography, Palaeoclimatology, Palaeoecology, 147*, 151–167.

Pascher, G. A. (1999). Geologische Karte des Burgenlandes. 1:200 000. Geologischen Bundesanstalt.

Szideczky-Kardoss, E. (1941). Ancient rivers in Transdanubia [Ősi folyók a Dunántúlon]. *Földrajzi Értesítő, 6*, 119–134. (in Hungarian).

Wagner, T., Fabel, D., Fiebig, M., Häuselmann, P., Sahyc, D., Xue, S., & Stüwe, K. (2010). Young uplift in the non-glaciated parts of the Eastern Alps. *Earth and Planetary Science Letters, 295*(1-2), 159–169.