STREAM GRADIENT INVESTIGATION IN THE BÜKKALJA USING INTERPOLATED SURFACES

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Abstract

The geological, tectonic settings of an area can be examined with the analysis of drainage network. In the Bükkalja, the Miocene pyroclasts – mainly the welded ignimbrites – had taken decisive part in the evolution of drainage network. For the confirmation of their role, the breakpoints of stream profiles were analysed. However this method provides information only about the direct surroundings of the creeks. In the aim of getting informations about the areas between the streams, surfaces were interpolated from stream gradient data and analysed as stream gradient maps. The stream gradient data were calculated with Hack J.T.'s formula, but due to the false results it was necessary to modify this formula and to recalculate the values. According to the map interpolated from the modified stream gradient values, there is a clearly identifiable relationship between the location of the welded ignimbrites on the surface, and the gradient values. Areas with high values are on the eastern part of the study area, where these pyroclasts can be found, while in the west, where the surface is covered by less resistant rock types, the gradient values are much lower.

Keywords: stream profile, stream gradient map, Bükkalja, ignimbrite, GIS

1. Introduction

Analyzing stream profiles in two dimensions is a useful tool to make relevant conclusions for the geological set-up and structure, for the tectonic deformations of an area (Gábris, 1986; Szabó, 1993; Troiani and Della Seta, 2008; Singh and Awashti, 2010). The longitudinal river profiles can display watershed landscape characteristics (Lee and Tsai, 2010). It is also applicable in the investigation of reach character, sediment characteristics and the age of streams (Gábris, 1986).

For the quantitative characterization of stream gradient conditions, the stream lenght-gradient index (SL index) is used (Pérez-Peña et al. 2008). This index was developed by Hack (1973). The SL index highlights gradient changes in stream channels. It is very sensitive to changes in lithology and tectonic uplift, so it can be very useful to detect tectonically active regions, tectonic displacements (Brookfield, 1998; Chen et al. 2003; Bishop et al. 2005; Goldrick and Bishop, 2007; Troiani and Della Seta, 2008; Tsodulos et al. 2008).

Comparing the adjacent streams slope gradient data, we can determine the character of the areas between the valleys, and conclusions can be drawn for the whole area. Analizing the spatial variation of the stream gradient data in a given area allows the recognitions of geomorphological processes and regional characteristics. With the use of stream gradient data a stream gradient map can be calculated. With the use of this map the drainage network can be analized already in three dimensions (Gábris, 1986).

In this paper the role of the Miocene welded ignimbrite cuestas is tried to be investigated in the evolution of drainage network of Bükkalja with the sketching of stream profiles and with the analysis of stream gradient map. Most of the streams in the Bükkalja are arriving from the North. In the study only the stream sections situated inside the boundary of territory have been examined, because the effect of pyroclastic rocks on the stream slopes prevail only there. On the basis of stream gradient map tectonic movements are tried to be investigated as well, which are often undetectable by other morhotectonic parameters (Troiani and Della Seta, 2008). There is a certain relationship between stream gradient maps and slope maps derived from digital elevation models (the correlation between the relief, slope and stream gradient maps was also analysed): the more valleys are examined, the resulting stream gradient map is more similar to the area's slope map. However the regional processes (e.g. tectonic uplifts, effects of rock quality) often can be investigated better with a less detailed stream gradient map. Therefore in this study only the main valleys of permanent creeks were used for the interpolation.

2. Study area

The Bükkalja is the largest mountain margin pedimentation in the North Hungarian Mountain Range, in fact in the whole Hungarian Mountains. Its area is 813 km². The geological structure is determined mainly by pyroclastic rocks, which built up the wide central part of the territory (Fig. 1). These rhyolite, rhyodacite and dacite tuffs, ignimbrites and welded (rheo)ignimbrites were formed in three sections during the Miocene (Pentelényi, 2005). Among these pyroclasts the welded ignimbrites are the "hardest", the most resistant rocks against erosion. For detailed examinations of rock quality, refer to documented experiments (e.g. Kertész, 1959; Kleb, 1999; Dobos, 2000; Kleb and Vásárhelyi, 2003). The long cuestas of these lava rock hardness welded ignimbrites – directed towards SWW-NEE − took decisive part in the evolution of the Bükkalja valley system (Hevesi, 2002), and also in the development of the pedimentation (Dobos, 2000; Pinczés et al. 1993). North of the ignimbrites the Bükkalja is joined to the Mesozoic rocks of the South-Bükk Mountains with a narrow, interrupted, old-Tertiary band of sediment: Eocene gravel, conglomerate and breccia, mottled clay; Upper-Eocene limestone, marl, clay marl; Oligocene clay, marl, clay marl, flint, sand and sandstone. To the south

the pedimentation inclines to the Borsod Plain (part of Great Hungarian Plain) with Pannonian- early Pliocene marine and Pleistocene terrestrial deposits: Lower-Pannonian sand, sandstone, mottled clay, clay marl; Upper-Pannonian sand, clay, gravel and layers of brown coal; Pleistocene gravelled-sanded deposits and loess (Pentelényi, 2002).
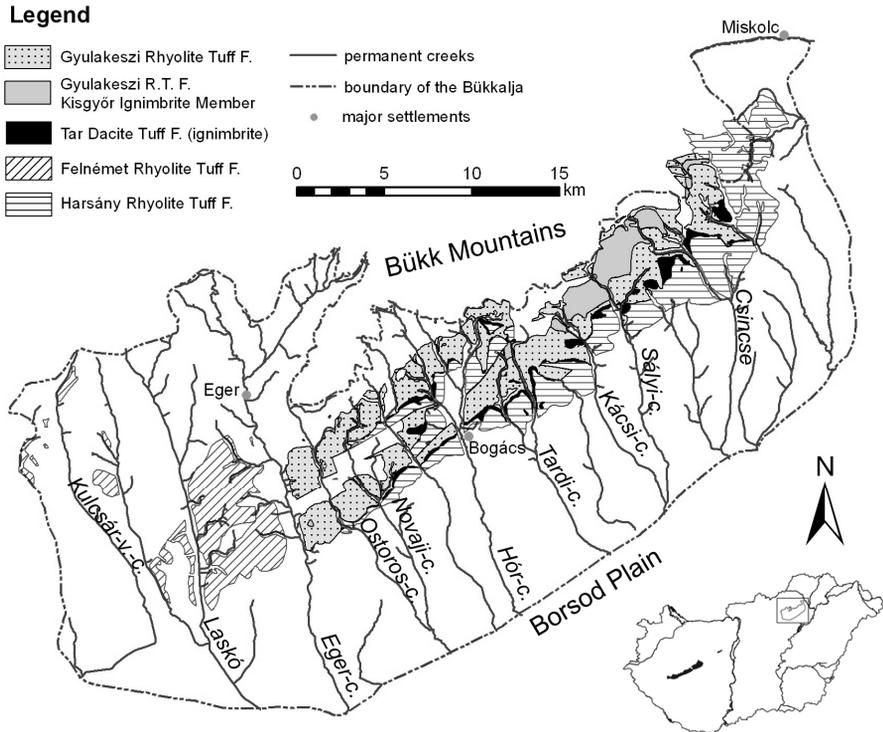

Fig. 1. Occurance of Miocene volcanic rocks and the stream network of Bükkalja (Pentelényi, 2002)

3. Methods

A point database was developed for the interpolation. The points were recorded on the basis of a 1:10,000 scale topographic map, in the intersections of the streams (determined and digitized by the blue-line method) and all of the 5 meter contour lines. The applied GIS software was the ESRI ArcGIS 9.3. Because of the relatively small differences in the elevation values, and the low stream gradients, and in order to have a sufficient number of data for interpolation it was necessary to assign the points with small elevation distances. With this method, 406 points were recorded on the 897 km^2 large area (average density: 0.45 points/km^2; Fig 2). According to Gábris (1986) this density and distribution is good enough to create reliable stream gradient maps. In each point the rate of the stream gadient was

measured with the Hack formula, these values were added as an attribute to the points. The measuring points appointed along the streams could be spatially displayed according to their coordinates. On the basis of the points coordinates and the stream gradient values a surface was interpolated, which can be analysed as a stream gradient map. For the interpolation a spline interpolation method (ArcGIS Spatial Analyst Modul "Spline with Barriers" method) was chosen which interpolates a smooth surface from points using barriers. In this case the barrier was the boundary of Bükkalja. The disadvantage of the applied method is, that the accuracy of interpolated surface mainly depends on the number and location of measuring points. In the Bükkalja the density of drainage network is different to the North and to the South from the welded ignimbrite cuestas (Vágó, 2006). Therefore the density and distribution of measuring points are neither equable: on the northern part of the pediment because of the higher drainage density the stream gradient can be measured in more points, than on the southern territory. Accordingly the interpolated surface is more detailed on the North. Through the data collecting method, the geomorphological, tectonical processes in the valleys can be more accurately determined, while on the kilometers wide interfluve hills these processes can be much less concluded. Despite the above mentioned disadvantages the regional observations in reference to the rock quality, or tectonic movements can be drawn. For the sake of the easier analysis, the isolines connecting the locations with the same stream gradients were also visualised on the interpolated surface.
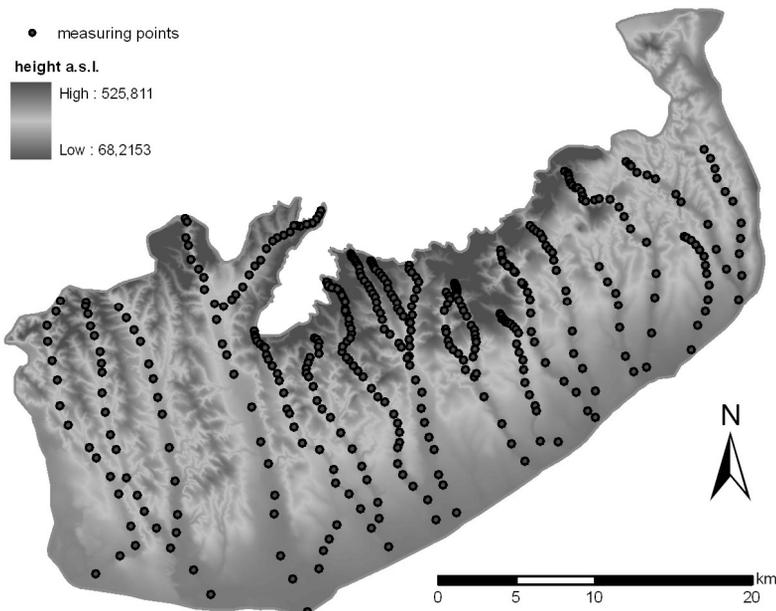

Fig. 2. Location of stream gradient measuring points and the digital elevation model of the Bükkalja

4. Results and discussion

4.1. Longitudinal profile analysis

On all of the creeks' stream profiles smaller-bigger breaks can be seen. There is no any stream in the area with normal, fully graded profile, even in the case of the oldest watercourses, like the Eger-, Laskó- (Láng, 1954; Pinczés, 1957; Hevesi, 1978) and Hór-creek (Pinczés, 1955) can be observed smaller changes in the profiles as well. According to the geological maps the definite breaks in the stream profiles can be explained mainly with the position of boundaries of different rock stripes (junctions), so in most cases these boundaries, the geological structures can be detected along the profiles. However, the fault lines do not appear directly on the profiles (only indirectly, because in many parts of Bükkalja rock stripes were risen along these faults above their northern surroundings). In the section of pedimentation between Kácsi- and Ostoros creeks the location of these tectonic movements can be identified in two, sometimes in three parallel stripes. In these cases the fault lines are boundaries between the different rock types as well (Fig 3).

Fig. 3. Geological cross section of the Bükkalja between Bükkzsérc and Tard (Pentelényi, 2005)
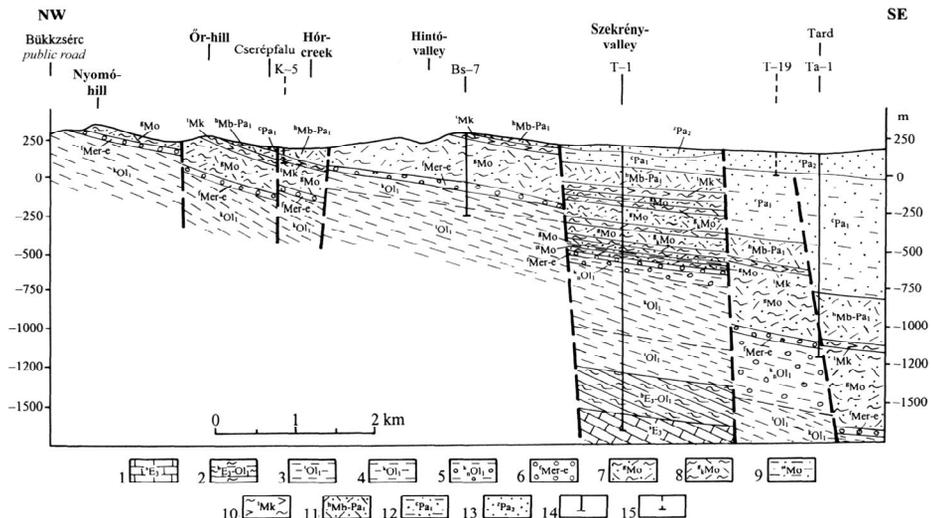
1 – Szépvölgy Limestone Formation, 2 – Buda Marl Formation, 3 – Tard Clay Formation, 4 – Kiscell Clay Formation, 5 – Kiscell Clay Formation, Noszvaj Member, 6 – Felsőnyárád Formation, 7 – Gyulakeszi Rhyolite Tuff Formation, 8 – Gyulakeszi Rhyolite Tuff Formation, Kisgyőr Ignimbrite Member, 9 – Salgótarján Lignite Formation, 10 – Tar Dacite Tuff Formation, 11 – Harsány Rhyolite Tuff Formation, 12 – Csákvár Clay Marl Formation, 13 – Zagyva Formation, 14 – borehole, 15 – borehole data projected to the section

Those creeks have the least graded, multiple broken profiles which flow across the "hardest", welded ignimbrite cuestas of Bükkalja. This rock type belongs to the most resistant stones of the territory (Fig 1). The changes in the steepness of stream

profiles are the greatest in the surroundings of these stone stripes. In the northern foreland of the welded ignimbrites, where the creeks are forced to pass round the relatively higher (~100-150 m) blocks of ignimbrite stripes, the creeks flow along very small relative relief. On the reaches, where the creeks cut through the ignimbrite stripes their stream gradient rises drastically. At the southern edge of these lava hard rock stripes the stream gradient reduced again. The most spectacular example is the Tardi-creek (Fig. 4), where the junctions can be clearly identified: the Upper-pass between ~0.5-1 km, and the Lower-pass between ~3-4 km.
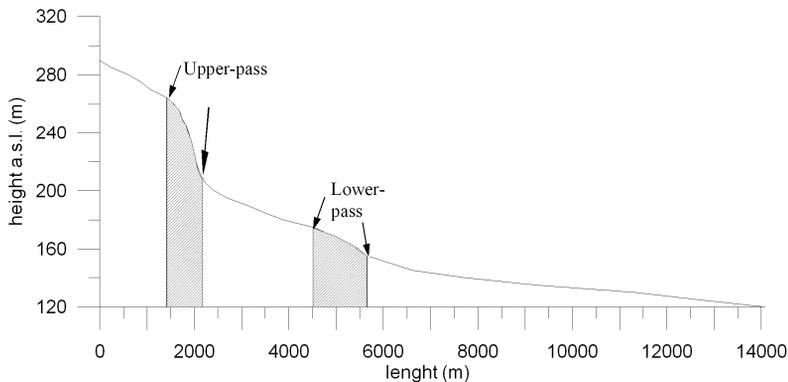

Fig. 4. Stream profile of the Tardi-creek showing the sharp changes in the steepness of the profile.

Similar breaks can be observed in the case of Cserépváraljai-, Kácsi-, Kulcsár-, Novaji- and Sályi-creeks stream profiles as well. Some creeks passing the ignimbrite stripes do not have sharp changes in their profiles: in the case of Hór-, Kánya-, Csincse creeks the junctions already cannot be seen, probably because these watercourses are older, and/or have a greater discharge.

4.2. Quantitative determination of the stream gradient values

The simpliest way to determine the creeks' quantitative gradient is to calculate their total (given in m), or relative (given in m/km) gradient values. In this case only one value represents the whole watercourse, and these absolute or average values are awkward to describe the detailed conditions and the changes in the steepness of the gradient along the examined creeks. The required data can be generated with the following method: points can be appointed along the creeks, in which the stream gradient can be measured.

In the Bükkalja the gradient conditions were determined with this method, applying the formula of Hack (1973), and conclusions were drawn on the geomorphological processes. For a segment of a given stream, the SL is defined as (Hack, 1973):

$$SL = \frac{dH \times L}{dL}$$

where dH is the change of elevation, dL is the horizontal length of the segment, L is the total channel length from the midpoint of the segment where the index is calculated, upstream to the water divide (Font et al. 2010, Fig. 5).
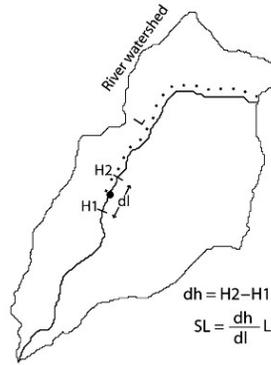

Fig. 5. Schematic diagram showing SL index calculation (Pérez-Peña et al. 2008)

In the course of the gradient value calculations (the value of "dH" was constantly 5 m, "dL" was calculated from the points coordinates) several errors occured in the database of the examined creeks' stream gradient values. Error may arise from the fact that the "L" (total channel length) value in the formula's numerator is growing from reach to reach towards the confluence of the creeks. According to the observations, in extreme cases it could happen, that at two consecutive reaches of the creek, where the horizontal distance (dL) is slightly smaller, or the same, the values of stream gradient are growing. Because "dH" is constant (5m), this error can occur only in consequence of multiplying with "L" (Table 1).

Table 1. Part of the Tardi-creek's stream gradient value database

height	dH	dL (m)	L (m)	SL index	modified SL index
145	5	509.2	5243.4	51.48	9.818
140	5	1079.5	6322.9	29.28	4.631
135	5	1536.2	7859.2	25.57	3.254
130	5	2060.1	9919.3	24.07	2.427
125	**5**	**1384.1**	**11303.5**	**40.83**	**3.612**
120	**5**	**1395.0**	**12698.5**	**45.51**	**3.584**

Another error arising from the application of "L" value in the formula is, that on the upper, steeper reaches of the creeks, where the gradient is much higher indeed, the stream gradient values are smaller, than on the lower, flatter reaches near to the mouth. According to Chen et al. (2003) the fact that the SL index is strongly influenced by river length makes comparing SL values in rivers of different length difficult. Other authors (Keller and Pinter, 2002), also observed, that the values of the index at the most distant stream reaches may include significant error.

Applying a modified parameter the above mentioned errors managed to exclude. This parameter determines the ratio of the relative relief and the horizontal distance of the examined points with the following formula:

$$SL_M = \frac{dH}{dL}$$

where dH is the change of elevation (in this case 5 m constantly), dL is the horizontal lenght of the segment in kilometeres. With this method the rate of the gradient can be given in m/km, and each watercourse have numerous gradient values. The difference between the "original" SL values, and the modified SL_M in the case of some streams is evident (Table 2).

Table 2. The SL, and modified SL stream greadient values of the major creeks in the Bükkalja

	SL index			modified SL index		
	Mean	min	max	Mean	min	max
Tardi-creek	48.18	13.00	125.10	45.41	2.43	148.81
Kácsi-creek	35.06	9.25	76.40	14.83	3.01	41.11
Sályi-creek	28.31	10.55	51.73	12.79	2.63	31.12
Csincse-creek	33.97	8.42	60.08	13.96	2.20	30.64
Kulcsár-völgyi-c.	20.07	6.71	41.30	8.57	2.23	27.13
Nyéki-creek	23.65	8.29	40.61	5.59	3.42	7.79
Ostoros-creek	38.36	8.84	88.50	11.56	3.13	32.46
Novaji-creek	34.24	9.05	66.49	10.63	3.18	24.96
Kánya-creek	65.01	11.47	183.86	16.56	3.65	53.67
Laskó-creek	30.26	8.93	66.92	3.89	1.92	6.13
Szóláti-creek	33.00	9.06	64.12	6.08	2.64	19.71
Kígyós-creek	33.40	10.24	79.76	4.01	2.32	6.52
Eger-creek	38.37	7.22	84.77	5.30	1.88	20.70
Szoros-creek	39.93	9.79	105.68	20.82	6.27	64.80
Cseresznyés-c.	35.93	13.47	79.81	20.10	10.22	46.19
Hór-creek	42.67	8.35	104.00	8.97	2.58	21.03
Cserépváraljai-c.	37.55	9.73	65.21	12.65	4.33	21.41

At the Tardi-creek (Fig. 6) the difference between the SL and modified SL values is particularly visible. The above mentioned errors of the calculations with the "original" SL formula is also visible: though the tendency of change is the same at either indices, but on the plot of the SL index the values near to the mouth are clearly higher, than at the headwaters of the creek; while the steepness of the modified SL index's plot is correct.
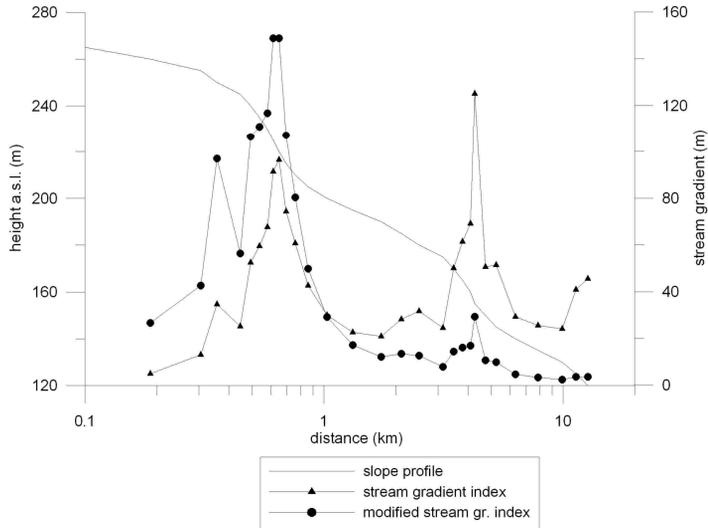

Fig. 6. The slope profile of the Tardi-creek, and the difference between the plots of the stream gradient and modified stream gradient indices

4.3. Spatial analysis of stream gradient conditions – stream gradient map

The stream gradient maps were created also on the basis of the SL index and modified SL index values, so the values of the two different calculations are spatially comparable. The most conspicuous difference between the maps is the really different position of the low and high gradient values: on the SL index map the higher values can be found on the southern, lower part of the Bükkalja (Fig. 7). According to the field observations and the slope map derived from the DEM (created from digitized 10m contour lines) of the territory, this result is evidently false, because in this area the gradient of the valleys and the interfluve hills is decreasing significantly.

On the contrary, in the map interpolated from the modified SL index values (Fig. 8) the higher values are situated on the northern, higher area of the pediment. However, the local definite changes, anomalies in the stream gradient values are clearly observable on both maps, moreover more or less at the same position. According to examinations in the study area, the SL index map and the resulting conclusions are not reliable in most cases: the local changes are indicated well, but

it is inappropriate to describe the tendencies on the whole area. Therefore I did not take this map into consideration at the analysis of the drainage network and the geomorphological processes. The reason for the unexplained changes in the stream gradient values (e.g. growing values towards the confluence) could be, that on the study area – compared to other areas (e.g. Börzsöny Mountains; Gábris, 1986), where the SL index resulted correct values – the relative relief is relatively low.
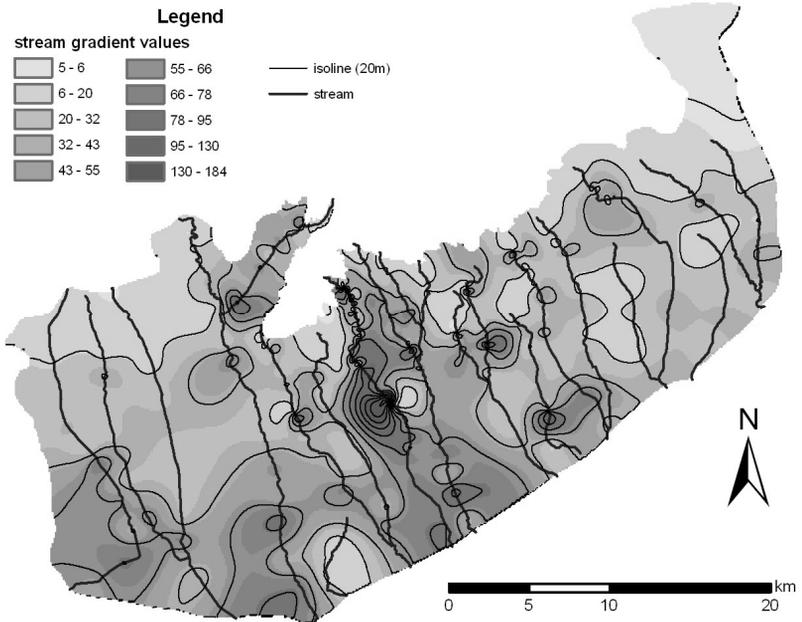

Fig. 7. Stream gradient map (SL index map) derived from the "original" SL index values (Hack, 1973)

On the basis of the modified stream gradient map (Fig. 8) the territory of the study area can be divided into two differing parts along the Eger-creek. The bulk of the high gradient values can be found to the east of the creek, while on the western part of the interpolated surface the values are much lower (less than 32 m/km). The highest values coincide with the occurrence of the Miocene welded ignimbrites, here the gradient is 23-133 m/km. The gradient is particularly high at the gorge-like valley sections of the Tardi-creek (Upper-, Lower Pass). Both passes are incised valley sections, built up by welded tuffs. Aside from rock qualities the extremely high values can be explained with the relief: the central part of the Bükkalja is a less dissected surface with higher average height (Hegedűs and Vágó, 2007), bounded by steep slopes. The height of this central area can be explained by young tectonic uplift. Gradient values between the Kánya- and Szoros-creeks, near to Borda-hill (276 m), are also the consequences of the welded ignimbrite's occurrence.
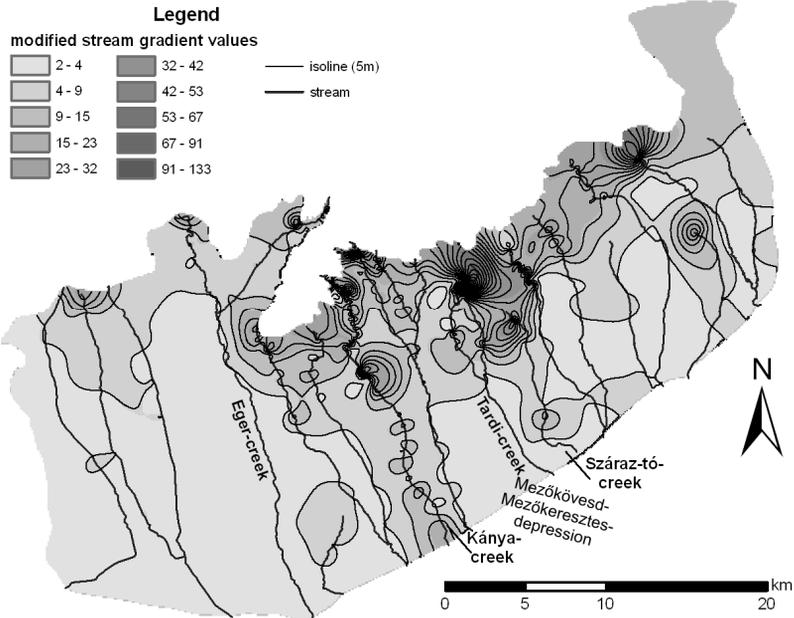
Fig. 8. Modified stream gradient map (modified SL map) derived from modified SL index values

In most of the valleys anomalies, increasing of gradient values can be examined (Fig. 8). However, the gradient of Kánya-creek is higher than the surroundings not only at its headwaters, but on its whole section, running across the Bükkalja. The reason of this is that Kánya-creek takes the biggest relative relief among the watercourses of Bükkalja: the headwater is situated on 350 m a.s.l. at the northern boundary of the study area, while – similarly to the adjacent creeks' valley floor – the confluence is on 120 m a.s.l. at the southern part of the area. The creek surmounts this significant relative relief not by short and steep sections, the incision is higher *along the whole valley* comparing to the surroundings. This can be explained with the creek's older age and/or bigger discharge.

The Száraz-tó-creek incisied at the headwaters into the rocks of the Harsány Rhyolite Tuff Formation, which is the least resistant rock formation to the erosion among the Miocene tuffs: the gradient is the biggest at this section of its valley. However, ca. 7 km away from the headwater, near to the southern margin of the pedimentation, an other area with relatively high gradient can be observed (15 m/km, which is 3-5 times bigger, than the gradients of the adjacent creeks). This blob signs the strong, local incision of the creek (Fig. 8), where the backward erosion is one of the greatest along the valley. The cause of it is probably the lowering of the southern foreground (Mezőkövesd-Mezőkeresztes depression), or the uplift of the northern terrain (Hevesi, 1978; Dobos, 2006). The same reaches of the adjacent watercourses (Kácsi-, Sályi-, Geszti-creek), where the stream gradients

are also slightly higher, than in the wider surrounding, support this assumption as well.

On the western part of the study area, the huge expanse of homogeneous, lower gradient values are conspicuous. On this area – except some smaller blobs – the stream gradient is only 2-4 m/km (Fig. 8). Exceptions are the surroundings of Kígyós-, Szóláti-, Laskó-creeks' headwaters, where on the dissected, relatively higher (average height) surface the gradient values reach the 20-24 m/km. The lack of the local anomalies with higher gradients confirms, that the quality and the resistivity of different rock types is not different significaly, at least crossing the junctions do not affects changes in the stream gradient.

Applying the ArcGIS 9.3. software "Band Collection Statistics" tool the Pearson's correlation coefficients between the datasets of modified stream gradient, slope, and relative relief were also calculated (Table 3). The slope and relief maps were derived on the basis of DEM created from 10 m contour lines. According to the calculations there is strong association between slope and relief values (r=0.85). There is only weak association between the slope and modified stream gradient map (r=0.29), and between the relief and modified stream gradient map (r=0.27). This points to the fact that the stream gradient is a new, independent variable which describes the surface differently. Due to this, it is possible to make geomorphologic examinations with this method from a different aspect.

Table 3. Correlation matrix of modified stream gradient, slope and relief values (p<0.05)

	Mod. stream gradient	Slope	Relief
Mod. stream gradient	1.00	0.29	0.27
Slope	0.29	1.00	0.85
Relief	0.27	0.85	1.00

It is proven that the analysis of stream gradient maps is a usefool method to examine landscape evolution, and the significance of lithology and tectonic movements (Gábris, 1986; Pérez-Peña et al. 2008). With this method observations of other authors (e.g. cosequence of tectonic movements, the evolution of Mezőkövesd-Mezőkeresztes depression, Dobos, 2006; Hevesi, 1978) managed to be confirmed from a different aspect. Conclusions for the role of lithology (resistance of welded ignimbrite cuestas) can be drawn as well, although other authors (Troiani and Della Seta, 2008; Font et al. 2010) draw attention to that it is difficult to examine the influence of lithology in the stream gradient values.

5. Conclusions

The main goal of this research was to examine the role of the geological settings of the Bükkalja in the development of drainage network. Beside the analysis of stream profiles, I tried to adopt a new method in the examinations: calculating the stream gradient values along the creeks in numerous points, a surface was interpolated, which was analysed as a stream gradient map. The main advantage of this method is, that – through the continuous surface – it provides informations also about the areas lying between the watercourses. Because of the false results received from the well known Hack formula, a new, modified formula was used for the calculations. Spatially visualising the stream gradient values, in the study area the evolution of drainage network, and the geomorphologic processes can be examined, determined, and observations in general scope can be done. Using this map, on the basis of stream gradient rates conclusions can be drawn also for the tectonic movements, or for the age of watercourses.

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