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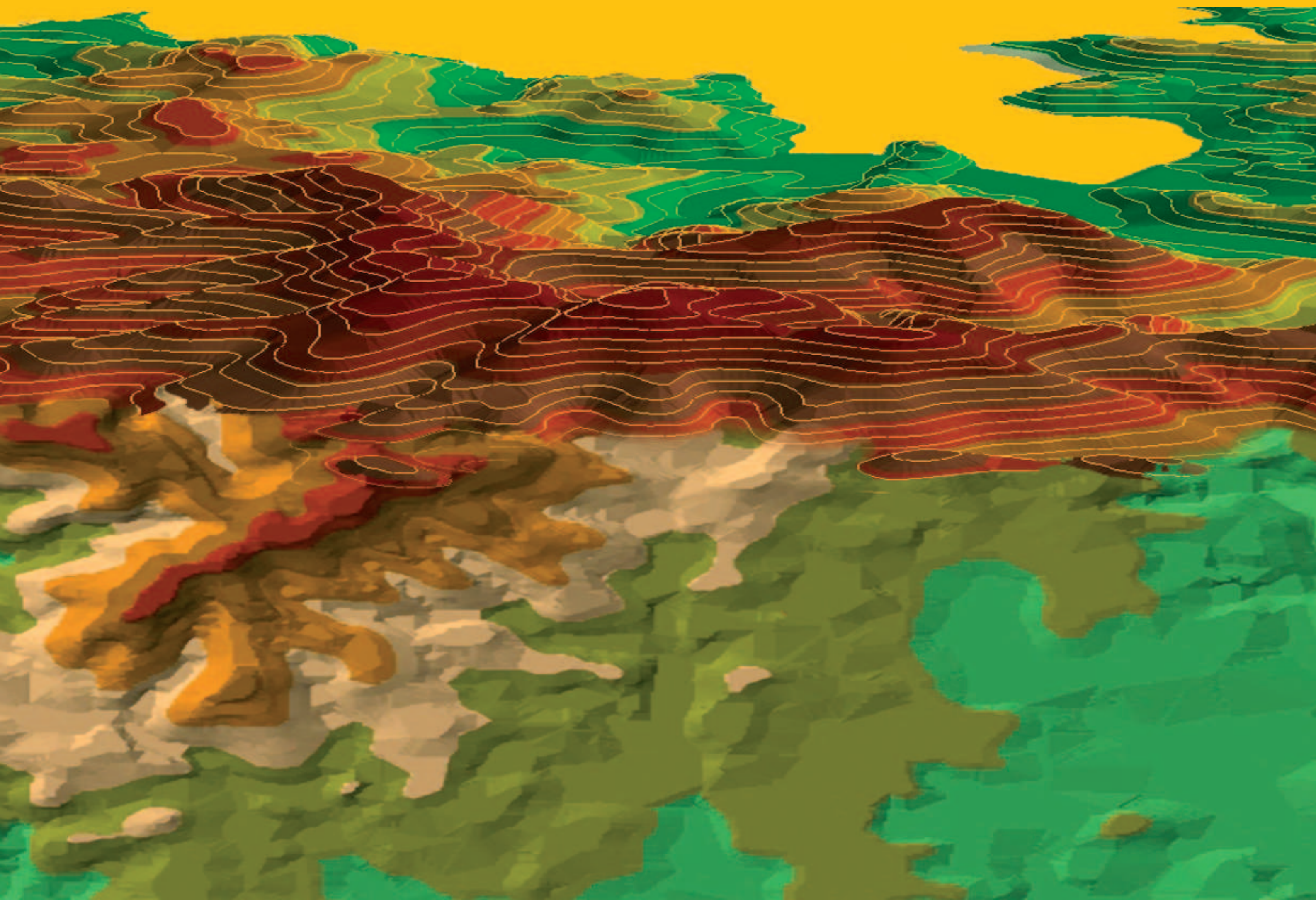

Fig. 10: Foliaged step-pools can also occur in wider stepped-bed streams under a deciduous forest canopy – the bankfull width corresponds to 4–5 meters in the Malá Ráztoka Stream (Moravskoslezské Beskydy Mts.; Photo: Zdeněk Přibyla)

Fig. 11: Flow concentration at the foliaged step (Photo: Zdeněk Přibyla)

Illustrations related to the paper by Z. Přibyla et al.

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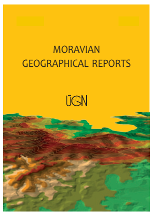

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GIS-based delineation of local climate zones: The case of medium-sized Central European cities

Jan GELETIČ [a *], Michal LEHNERT [b]

Abstract

Stewart and Oke (2012) recently proposed the concept of Local Climate Zones (LCZ) to describe the siting of urban meteorological stations and to improve the presentation of results amongst researchers. There is now a concerted effort, however, within the field of urban climate studies to map the LCZs across entire cities, providing a means to compare the internal structure of urban areas in a standardised way and to enable the comparison of cities. We designed a new GIS-based LCZ mapping method for Central European cities and compiled LCZ maps for three selected medium-sized Central European cities: Brno, Hradec Králové, and Olomouc (Czech Republic). The method is based on measurable physical properties and a clearly defined decision-making algorithm. Our analysis shows that the decision-making algorithm for defining the percentage coverage for individual LCZs showed good agreement (in 79–89% of cases) with areas defined on the basis of expert knowledge. When the distribution of LCZs on the basis of our method and the method of Bechtel and Daneke (2012) was compared, the results were broadly similar; however, considerable differences occurred for LCZs 3, 5, 10, D, and E. It seems that Central European cities show a typical spatial pattern of LCZ distribution but that rural settlements in the region also regularly form areas of built-type LCZ classes. The delineation and description of the spatial distribution of LCZs is an important step towards the study of urban climates in a regional setting.

Key words: *GIS, local climatic zone, LULC, urban climates, urban landscape, Czech Republic*

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1. Introduction

Local Climate Zones (LCZs) are defined as regions with a characteristic surface cover, structure, material, and human activity that span hundreds of metres to several kilometres on the horizontal scale (Stewart and Oke, 2012). The classification of LCZs is generic and allows inter-city comparisons. The classification was originally designed to standardise the description of urban climate research site characteristics, as Stewart (2011) had reported that up to three-quarters of Urban Heat Island (UHI) studies failed in the presentation of proper metadata. There are three key strands in terms of LCZ usage to date:

1. for UHI studies (e.g. Alexander and Mills, 2014; Emmanuel and Krüger, 2012; Leconte et al., 2015; Lehnert et al., 2015);
2. for modelling (Alexander et al., 2015; Bokwa et al., 2015; Geletič et al., 2016): and
3. for mapping intra-urban land cover (Bechtel and Daneke, 2012; Lelovics et al., 2014; Danylo et al., 2016).

Bechtel and Daneke (2012) and Lelovics et al. (2014) created the first LCZ mapping methods and moved the LCZ concept toward a generally recognised regional typology. With such a radical shift in the LCZ concept some new methodological problems appeared: the size of a spatial mapping unit (pixel size); the method used for generalisation; the temporal variability of the physical properties of the environment; the objectification and standardisation of the classification procedure; and other issues (Bechtel and Daneke, 2012; Lelovics et al., 2014; Lehnert et al., 2015).

In accordance with Gál et al. (2015), the approaches to LCZ mapping can be divided into the GIS-based method (Lelovics et al., 2014), the satellite imagery-based method (Bechtel and Daneke, 2012), and combined methods (Gál et al., 2015). In most recent research, there is an obvious effort to create a universal and widely available method for LCZ classification and mapping (Bechtel et al., 2015). At the same time, Alexander et al. (2015) point out that the further use of LCZs, for example for climate modelling, is limited by the considerable subjectivity in the definitions.

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The main objective of this study is to introduce and verify a new concept of a GIS-based method, based on a clearly defined decision-making algorithm for Central European cities, which may address all the above-mentioned points concerning the LCZ usage: UHI studies, climate modelling, and mapping intra-urban land cover in the region. Another partial aim of the study is to apply the classification to one of the suggested uses – analyses of intra-urban and inter-urban land cover based on the cases of three medium-sized Central European cities. The remaining points of LCZ applications – UHI studies and climate modelling – will be addressed in future papers.

2. Methods

2.1 Mapping of local climate zones

The method used for the delineation of local climate zones presented here was developed and tested in the area of Brno and its surroundings (Czech Republic). It was validated in the cities of Hradec Králové and Olomouc and their surroundings (Czech Republic): see Table 1 and Figure 1. These experimental areas were chosen because:

a. they represent typical Central European cities with a varied mix of buildings, representing various historical periods in urban development (an historic centre, parks, residential buildings, industrial parks, housing estates, modern shopping centres and stores, satellite development and allotments); and

b. research on the urban climate is being carried out in all three cities and their surroundings by Dobrovolný et al. (2012) in Brno, Vysoudil et al. (2012) in Olomouc, and Středová et al. (2015) in Hradec Králové.

For the development of a new LCZ classification approach, it was essential to use objective physical parameters of the environment with values that are quasi-invariable over time that can be measured with sufficient accuracy, and are relatively easy to measure. From the values of geometric and surface cover properties and the values of thermal, radiative, and metabolic properties designed for the individual LCZs by Stewart and Oke (2012), there were four parameters meeting the criteria: building surface fraction (BSF), impervious surface fraction (ISF), pervious surface fraction (PSF), and the height of roughness elements or, more specifically, the geometric average of building

Location*	Size of experimental area (km)	Size of compact urban development (ha)	Population	Average elevation (m)	Lattitude (city centre)	Longitude (city centre)
Brno	25.0 × 25.0	8,266	400,000	259	49°12′ N	16°37′ E
Hradec Králové	11.0 × 9.0	2,835	92,000	235	50°13′ N	15°50′ E
Olomouc	14.6 × 14.3	2,954	102,000	219	49°36′ N	17°15′ E

Tab. 1: Basic data for the experimental areas
*Note: * including city and the surroundings. Source: authors' elaboration*

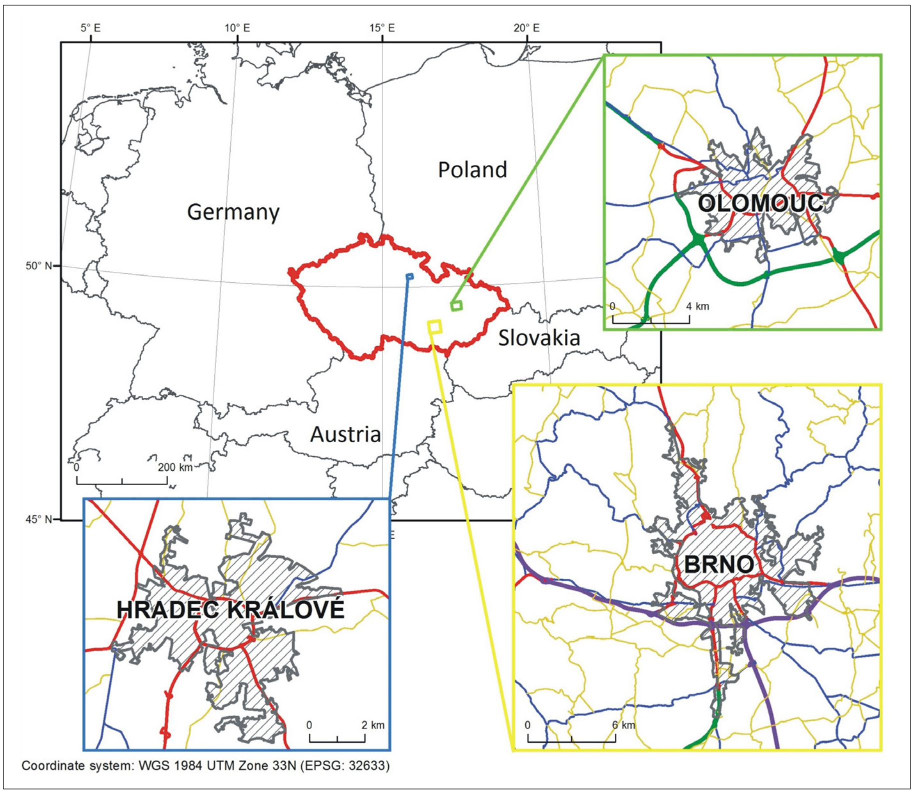

Fig. 1: The location of Brno, Hradec Králové, and Olomouc in Central Europe and the delineation of the experimental areas and compact urban development. Source: authors' elaboration (basic data: National geoportal INSPIRE)

heights (HRE). Since these parameter values overlap for some zones, the zones were differentiated using one of the remaining physical properties of the environment, and in these cases, we have introduced derived and easily detectable parameters (not explicitly mentioned by Stewart and Oke (2012), but inherent in their classification scheme). An overview of all the parameters used here is presented in Table 2. LCZs classes schema designed by Stewart and Oke (2012) is presented in Figure 2.

To differentiate the specific LCZs of built-type classes, we applied the parameter of the number of buildings per hectare (NoB). Similarly, to differentiate the specific LCZs of land cover type classes, we applied the derived parameters: PSFs as the percentage of surface covered by bare ground from an aerial view of the total PSF; PSFl as the percentage of surface covered by low vegetation (< 2 m) from an aerial view of the total PSF; PSFh as the percentage of surface covered by high vegetation (> 2 m) from an aerial view of the total PSF; PSFw as the percentage of the surface covered by water from an aerial view of the total PSF; NoC as the area of continuous crown cover surface above 2 m per 1 ha from an aerial view; and NoV as the number of continuous fragments of all vegetation per 1 ha from an aerial view (regardless of vegetation nature and height).

For the classification process, as a surface unit carrying the physical parameters of the environment, we chose a pixel of one hectare (100 × 100 m) as the theoretically mean smallest relevant spatial unit, in which the physical properties of the environment significantly affect air temperatures (energy fluxes) at a local level (see Schmid et al., 1991; Merbitz

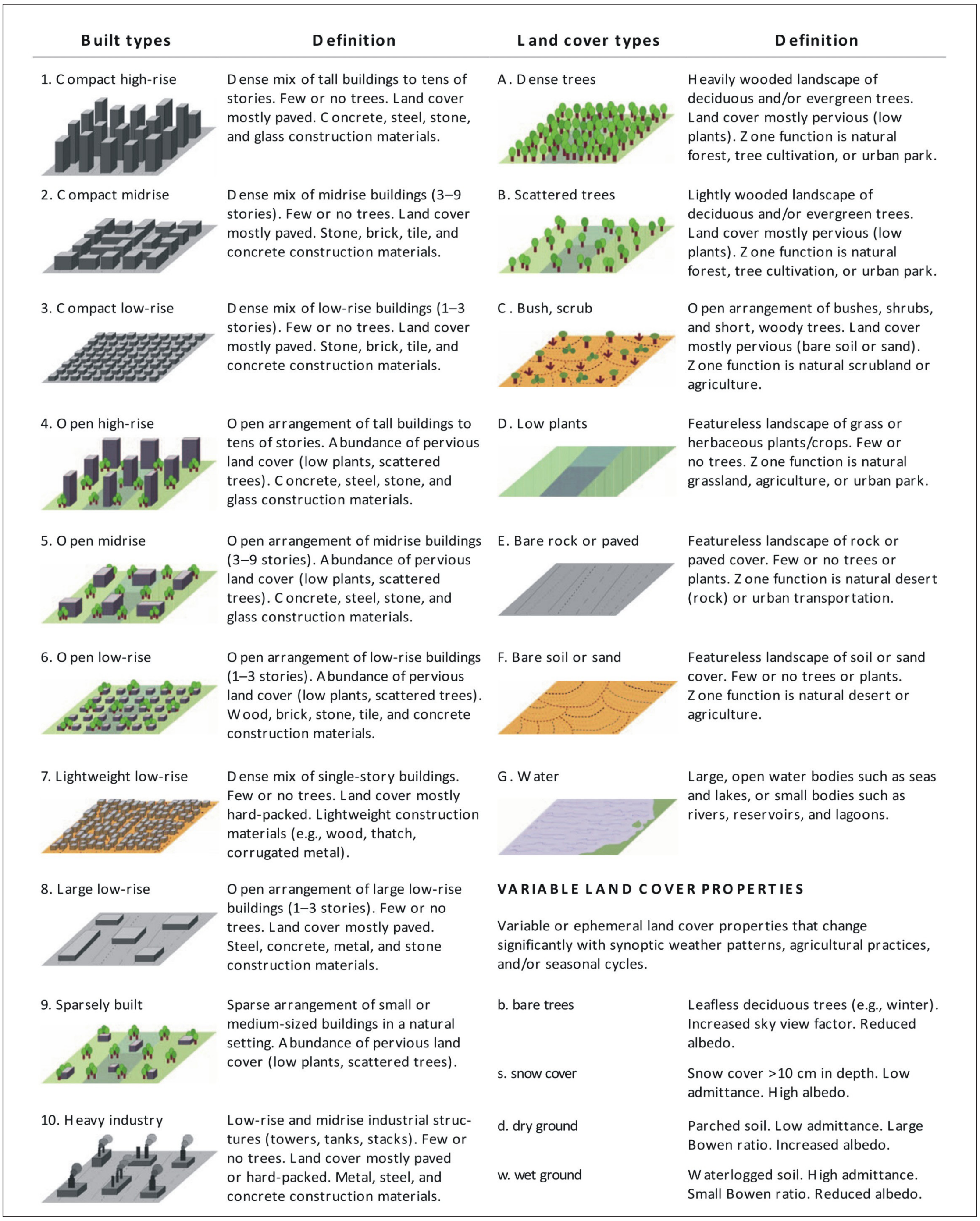

Fig. 2: Description of LCZ classes defined by Stewart and Oke (2012)
Source: Stewart and Oke (2012)

et al., 2012; Gál et al., 2015). The methodological procedures used in the proposed LCZ mapping method are described in four consecutive steps: 1) preparation of input data; 2) classification procedure; 3) filtering and after-processing, and 4) validation and comparison.

2.1.1 Preparation of input data

For easy delineation of the areas with PSF, BSF, and ISF (and hence for the determination of the percentage of PSF, BSF, and ISF in each 100-m pixel), it proved favourable to use an existing geodatabase (Leconte et al., 2015; Alexander and Mills, 2014). In our case, it was the ZABAGED geodatabase (ČÚZK, 2015) distinguishing 116 categories of well-targeted geographical objects and fields (e.g. built-up areas, communications, hydrology, vegetation, and surface), which were tested and subsequently reclassified for BSF, PSF, and ISF at high accuracy (Fig. 3). Automatically generated results of the reclassifications were checked and where necessary, BSF, PSF, and ISF borders were controlled (and corrected if necessary) using aerial imagery (ČÚZK, 2015). The accessibility of ZABAGED (for the Czech Republic) or a similar geodatabase (for other Central European countries) is crucial for the application of the LCZ classification approach presented below.

For the cities of Brno and Hradec Králové and their surroundings, the information on the height of buildings (HRE) was obtained from existing photogrammetric data.

Parameter	Description	Possible Sources
BSF	Building surface fraction (%)	OSM, local land registry office, national LULC databases, derivations from aerial imagery
HRE	Geometric average of building heights (%)	OSM, local land registry office, photogrammetric mapping
ISF	Impervious surface fraction (%)	OSM, national LULC databases, derivations from aerial imagery
NoB	Number of buildings per hectare	OSM, local land registry office, national LULC databases, derivations from aerial imagery
NoC	Number of areas of continuous surface of crown cover above 2 m	Photogrammetric mapping outputs, derivations from aerial imagery (less accurate)
NoV	Number of continuous fragments of all vegetation per ha	Derivations from OSM, national LULC databases
PSF	Pervious surface fraction	Derivations from OSM, national LULC databases
PSF_h	Surface covered by high vegetation (%)	Derivations from OSM, national LULC databases
PSF_l	Surface covered by low vegetation (%)	Derivations from OSM, national LULC databases
PSF_S	Surface covered by bare ground (%)	Derivations from OSM, national LULC databases
PSF_w	Surface covered by water (%)	Derivations from OSM, national LULC databases

Tab. 2: Overview of parameters used in the decision-making algorithm for classifying pixels into local climate zones
Note: OSM – OpenStreetMap; for more details see Over et al. (2010). Source: authors' elaboration

Fig. 3: Categories of building surface, impervious surface, and pervious surface after the reclassification of ZABAGED (left) and its checking against the background of an aerial image (right)
Source: authors' elaboration (basic data: ZABAGED and Orthophotomap are provided by ČÚZK, 2015)

For the city of Olomouc and its surroundings, we used a block model applying an algorithm working with OpenStreetMap (OSM); for more details see Over et al. (2010).

While approximately 20% of buildings in OSM lacked the height information, the missing data were derived from the available information about floors each building has. The building-height layer was then paired with the BSF areas. In the next step, we calculated the average height of the buildings in a pixel, which was determined as a weighted mean of the heights of all buildings extending into the pixel, weighted by the ground area of the building. The information on the number of buildings in the pixel (NoB) was easily derived from the paired layer of building heights. For pixels in undeveloped areas (land cover types), it was also necessary to determine the values of NoC, NoV, PSFh, PSFl, PSFs and PSFw, which were detected by means of the manual editing of ZABAGED over an aerial image.

2.1.2 Classification procedure

Following the method for data preparation outlined previously, we were able to obtain a layer of 100-m pixels containing information about the internal structure of each pixel. Subsequently, we used the algorithms described below and reclassified (in the R program) all the pixels from this layer into their respective LCZs (Fig. 4, Tab. 2).

In Step 1 of the decision-making algorithm, only the BSF parameter was used. Where the representation of BSF in a given pixel was > 10%, the pixel (x) was further classified into the LCZ *built types* classes (LCZ_{bt}) in accordance with the typical intervals of BSF values proposed by Stewart and Oke (2012), while in the case of BSF ≤ 10, the pixel was classified into the LCZ *land cover type classes* (LCZ_{lct}), as follows:

$$\forall x: (x \in LCZ_{bt} \Leftrightarrow x_{BSF} > 10) \vee (x \in LCZ_{lct} \Leftrightarrow x_{BSF} \leq 10) \quad [1]$$

The pixels categorised into LCZ_{bt} in Step 1 were further classified in accordance with Step 2a, where the individual LCZs were distinguished using the BSF, ISF, PSF, and HRE parameters. First, for each of those parameters we calculated DIF as an absolute difference between the value of the parameter in the pixel and the nearest outer (upper – UL or lower – LL) limit of the interval of typical values of the parameter for each particular LCZ_{bt}.

$$\forall x \in LCZ_{bt}: \left(x_i \in \langle DH_{iLCZ_j}; HH_{iLCZ_j}\rangle \Rightarrow DIF_{iLCZ_j} = 0\right) \vee \vee \left(x_i \ \min\left\{\left|x_i - LB_{iLCZ_j}\right|; \left|x_i - UB_{iLCZ_J}\right|\right\}\right), \quad [2]$$

where $i \in$ {BSF; PSF; ISF; HRE} and $j \in$ {1; 2; 3; …; 10}.

Subsequently, we calculated the sum of DIF for each LCZ_{bt}, and the pixel was classified in the LCZ with the smallest sum of DIF. To deal with different units and scales of parameters we came up with the number 6 for multiplying the DIF of HRE. This value was based on standardisation and analysis of the importance of each factor for the final classification (in a simplified way, the origin of this value reflects the scale differences between BSF, ISF, PSF, and HRE and equalizes the weight of the parameters, which indicates the properties of the space in the horizontal (BSF, ISF, and PSF) and vertical (HRE) dimensions). Therefore:

$$\forall x \in LCZ_{bt} \ \exists \ LCZ_j: x \in LCZ_j \Leftrightarrow DIF_{BSF_j} + DIF_{ISF_j} + + DIF_{PSF_j} + 6 \times DIF_{HRE_j} = \min, \quad [3]$$

where $j \in$ {1; 2; 3; …; 10}.

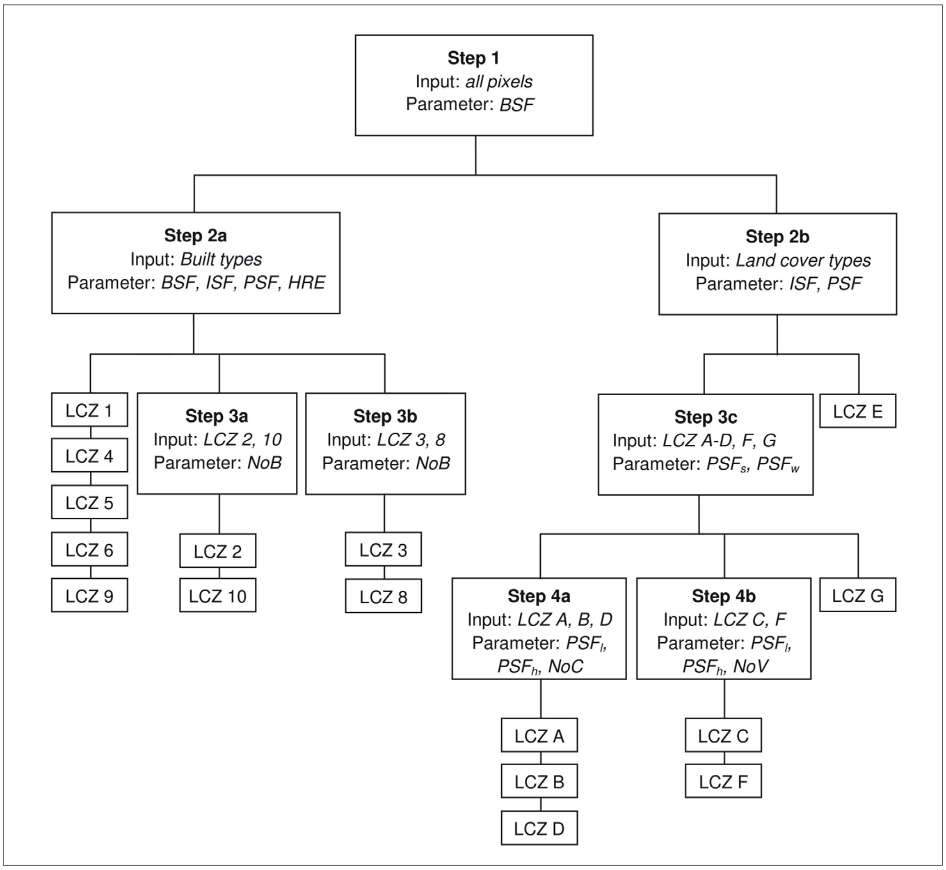

Fig. 4: The scheme of the proposed decision-making algorithm for classifying pixels into local climate zones (LCZ)
Source: authors' elaboration

If a pixel fell into LCZ 1, 4, 5, 6, or 9, it was left in that zone. If a pixel fell into LCZ 2, 3, 8, or 10, it was processed within Step 3 of the decision-making algorithm since, using the parameters BSF, ISF, PSF, and HRE, it was not possible to differentiate whether a pixel belonged to LCZ 2 or 10 and 3 or 8. Therefore, in Step 3 we used the NoB as a decisive parameter, which distinguished whether the BSF in the area (pixel) consisted mainly of large warehouses and factory halls or rather of much smaller houses. Therefore, when deciding between LCZs 3 and 8 (Step 3b), if the NoB was smaller than 18, the pixel belonged to LCZ 8, and if the NoB ≥ 18, the pixel belonged to LCZ 3. Therefore:

$$\forall\, x \in LCZ_3 \cup LCZ_8\colon (x_{NoB} < 18 \;\Rightarrow x \in\; LCZ_8) \vee \vee\, (x_{NoB} \geq 18 \;\Rightarrow x \in\; LCZ_3) \quad [4]$$

Similarly, when deciding between LCZ 2 and 10 (Step 3a), if the NoB was smaller than 11, the pixel belonged to LCZ 2, and if the NoB ≥ 11, the pixel belonged to LCZ 10. Therefore:

$$\forall\, x \in LCZ_2 \cup LCZ_{10}\colon (x_{NoB} < 11 \;\Rightarrow x \in\; LCZ_{10}) \vee \vee\, (x_{NoB} \geq 11 \;\Rightarrow x \in\; LCZ_2) \quad [5]$$

The threshold values for Steps 3a and 3b were based on the analysis of the numbers of buildings in pixels, which were typical of the built-up areas in LCZs 2 and 10 and LCZs 3 and 8 in Brno. For the proposed decision-making algorithm LCZ 7, i.e. Lightweight Low-rise, which generally refers to informal housing, was not included as this specific LCZ did not occur widely across the selected test cases. Future iterations of the algorithm will aim to include this.

For pixels, which were classified in LCZ_{lct} in Step 1 of the decision-making algorithm, Step 2b was applied. In Step 2b, the parameters ISF and PSF were used to distinguish whether the pixel fell into the LCZ E class or other classes of LCZ_{lct}. If the ISF was higher than the PSF, it fell into LCZ E; if it was lower, the pixel fell into other classes of LCZ_{lct}, as follows:

$$\forall\, x \;\in\; LCZ_{lct}\colon x \in LCZ_E \;\Leftrightarrow\; x_{ISF} >\; x_{PSF} \quad [6]$$

If the pixels fell into another class of LCZ_{lct} in Step 2b, they were classified further in Step 3c. In Step 3c the parameters PSFS and PSF_w were adopted to distinguish whether the pixel fell within LCZ G, i.e. whether it would be classified according to Step 4a or 4b within the fourth step of the classification procedure, as follows:

$$\forall x \in LCZ_{lct} - LCZ_E\colon \left(x \in LCZ_G \Leftrightarrow x_{PSF_w} \geq 50\right) \vee \vee \left(x \in\; LCZ_C \cup LCZ_F \;\Leftrightarrow\; x_{PSF_s} > 50\right) \vee \vee \left[x \in\; LCZ_A \cup LCZ_B \cup LCZ_D \;\Leftrightarrow (x_{PSF_w} < 50 \wedge x_{PSF_s} < 50)\right] \quad [7]$$

If a pixel was classified according to Step 4a in the fourth step of the classification procedure, then the decisive parameters were PSF_l, PSF_h, and NoC, as follows:

$$\forall x \in LCZ_A \cup LCZ_B \cup LCZ_D\colon \left[x \in LCZ_A \Leftrightarrow x_{PSF_h} > 80 \vee \vee \left(x_{NoC} < 10 \;\wedge x_{PSF_h} > x_{PSF_l}\right)\right] \vee \left[x \in LCZ_A \Leftrightarrow x_{PSF_l} > > 90 \vee \left(x_{NoC} < 10 \wedge x_{PSF_l} > x_{PSF_h}\right)\right] \vee (x \in LCZ_B \Leftrightarrow \Leftrightarrow x \in LCZ_A \cup LCZ_D \;\wedge\; x_{NoC} > 10) \quad [8]$$

If a pixel was classified according to Step 4b in the fourth step of the classification procedure, the decisive parameters were PSF_l, PSF_h, and NOCs, as follows:

$$\forall x \in LCZ_C \cup LCZ_F\colon \left(x \in LCZ_C \Leftrightarrow x_{PSF_l} + x_{PSF_h} > 10 \;\wedge \wedge\, x_{NoV} > 15\right) \vee x \notin\; LCZ_C \Rightarrow x \in\; LCZ_F \quad [9]$$

2.1.3 Filtering and After-Processing

After all the pixels had been assigned to an appropriate LCZ, we were able to delineate the LCZ areas. First, we applied a two-stage focal analysis in the ArcMap (10.3.1) program on the majority principle; i.e. a pixel was assigned to an LCZ most frequently represented in its neighbourhood. Subsequently, areas sized less than a hectare were aggregated to an LCZ which prevailed in their neighbourhood, and finally the borders of the resulting areas were smoothed.

2.1.4 Validation and comparison

The classification procedure was developed within the territory of Brno and its surroundings, where we first tested the decision-making algorithm, optimal pixel size, various settings for the parameters of the zones, etc. In this respect, the area of the city of Brno and its surroundings could be regarded as a training area, while the areas of the cities of Hradec Králové and Olomouc and their surroundings might be considered independent test areas.

For each area of interest, we selected 10% of pixels, for which we evaluated the agreement of their classification in an appropriate LCZ as compared with their inclusion in an appropriate LCZ defined on the basis of expert knowledge. We determined the following:

- the overall producer accuracy prior to after-processing (percentage of classified cases which really belonged to the respective LCZ for pixels before filtering and after-processing according to expert knowledge), and
- the resulting overall producer accuracy following the after-processing (percentage of classified cases which actually belonged to the respective LCZ after filtering and after-processing according to expert knowledge).

Lastly, using the case of Brno, we compared the LCZ map based on our method (the version before after-processing) with an LCZ map created by the application of the Bechtel and Daneke (2012) methods. The application of the Bechtel and Daneke (2012) methods was based on five LANDSAT-8 scenes (2013-04-15, 2013-06-18, 2013-08-05, 2013-09-06, and 2014-05-20). In the first step, the images were reclassified to a 100 m resolution. They were provided from 3 to 7 training areas for each LCZ class regarding the complexity of surface characteristics of the given class. The Random Forest (ViGrA) algorithm (Bechtel and Daneke, 2012) was adopted as a classifier. Finally, a majority filter with different neighbourhoods of 200-m radius was applied. The results obtained through the method of Bechtel and Daneke were refined twice, improving the training data.

2.2 Analyses of the spatial distribution of LCZs

Based on the LCZ maps we generated for Brno, Hradec Králové, Olomouc and their surroundings, we evaluated the absolute (area) and relative (percentage) occurrence of LCZs in these three medium-sized Central European cities and their spatial pattern. The analyses were performed for areas with compact urban developments defined using the methodology of Halás et al. (2012), which is based on calculations of the average distance between buildings. The share of different climatic zones was then also evaluated in the surroundings of the cities, i.e. outside the compact urban areas.

3. Results

3.1 Delineation of local climate zones

Using the methods described above, we compiled LCZ maps for the three selected medium-sized Central European cities (see Fig. 5).

Table 3 shows typical values of the BSF, ISF, PSF, and HRE parameters for each LCZ identified in the Central European region. We intended to work primarily with the universal values proposed by Stewart and Oke (2012), but with respect to the classification procedure, we considered it necessary to take some specific regional features into account.

Specifically, it appeared that in the examined cities, LCZ 10 (heavy industry) was characterised by a higher percentage of BSF and ISF to the exclusion of PSF and by a generally higher HRE. Furthermore, it appeared that because of the morphological character of built-up areas in Central Europe (functionalist inter-block developments with extensive green courtyards, or housing estates with greenery established according to socialist concepts of urbanism), it was necessary to increase the upper limit of the interval of typical PSF values for the LCZs 4 and 5 for this region (Tab. 3). It was also shown that LCZ 7 (lightweight low-rise) did not occur in Central Europe, or more precisely, that the random signs did not create a sufficiently large spatial unit for which a local climate could be determined.

3.2 Comparison of cities and methods

The validation results indicated that our method for delineating the LCZs corresponded with expert knowledge in 79–89% of cases (Fig. 6). There were only slight differences in terms of classification accuracy (performance) between Brno and its surroundings, where the classification method originated, and Hradec Králové and Olomouc, where it was applied later (Fig. 6). This demonstrated the representativeness of the method for the Central European region. Considering the relevance at a spatial level of the local climate, it was essential that the suggested mapping method maintained high producer accuracy in general, i.e. regarding the final delineation of LCZ areas (overall producer accuracy after post-processing).

It turned out that there was compliance between areas defined by our GIS-based method and areas delineated by the satellite image-based method applied by Bechtel and

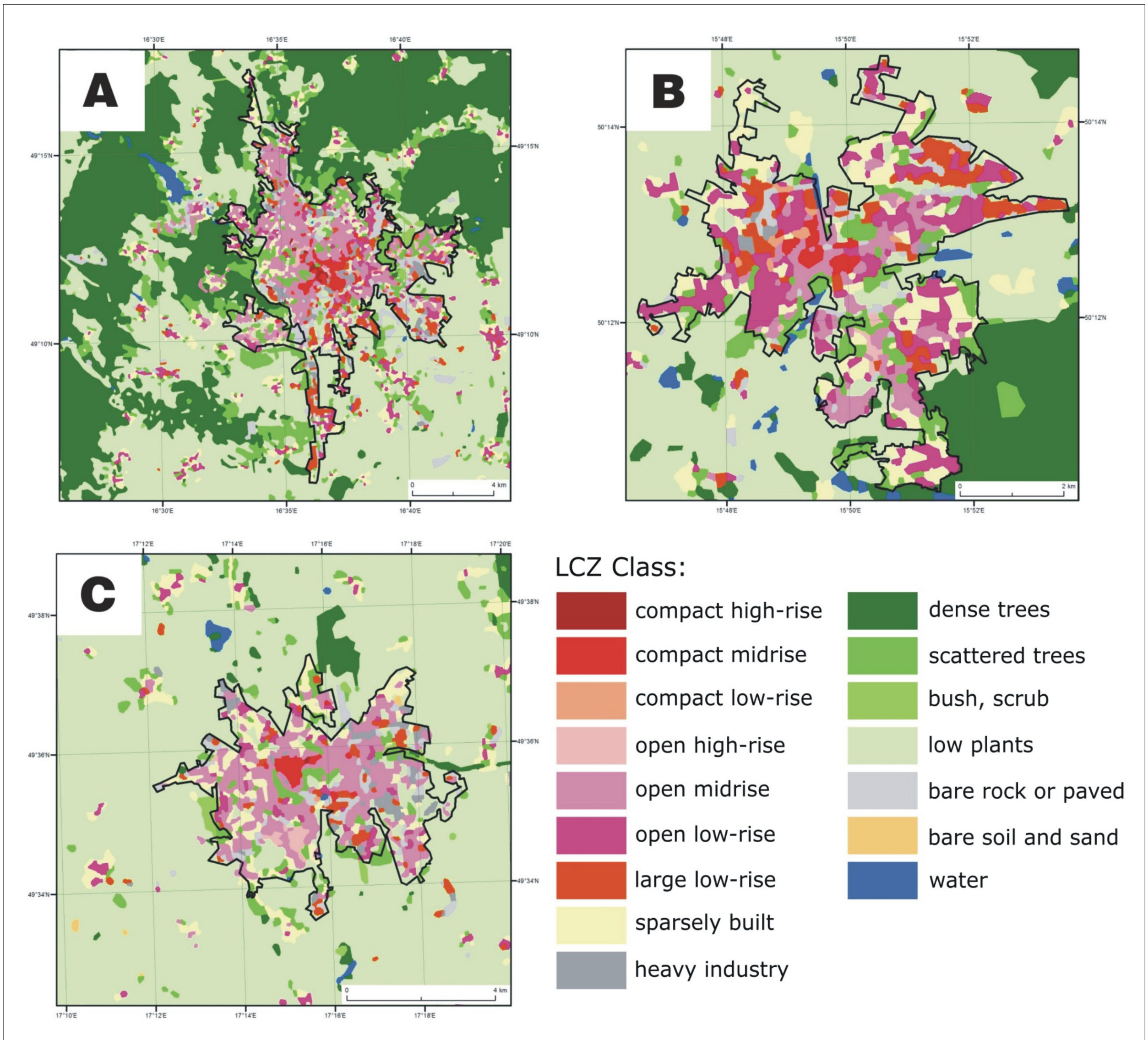

Fig. 5: Local climate zones in Brno (A), Hradec Králové (B), Olomouc (C) and its surroundings (Coordinate system: WGS 1984 UTM Zone 33N); black line represents compact city
Source: authors' elaboration

LCZ	BSF (%)	ISF (%)	PSF (%)	HRE (m)
1	40 – 60	40 – 60	< 10	> 25
2	40 – 70	30 – 50	< 20	10 – 25
3	40 – 70	20 – 50	< 30	3 – 10
4	20 – 40	30 – 40	30 – 50 (30 – 40)	> 25
5	20 – 40	30 – 50	30 – 60 (20 – 40)	10 – 25
6	20 – 40	20 – 50	30 – 60	3 – 10
8	30 – 50	40 – 50	< 20	3 – 10
9	10 – 20	< 20	60 – 80	3 – 10
10	40 – 70 (20–30)	30 – 60 (20–40)	< 10 (40 – 50)	10 – 20 (5–15)
A	< 10	< 10	> 90	3 – 30
B	< 10	< 10	> 90	3 – 15
C	< 10	< 10	> 90	< 2
D	< 10	< 10	> 90	< 1
E	< 10	> 90	< 10	< 0.25
F	< 10	< 10	> 90	< 0.25
G	< 10	< 10	> 90	–

*Tab. 3: Values of selected surface cover properties for local climate zones valid for the Central European region (After Stewart and Oke, 2012, modified). Note: * The values which were modified as compared to those given by Stewart and Oke (2012), are in bold, while the original values are in brackets.*
Source: Stewart and Oke (2012, modified

Daneke (2012) in the case of 51.1% of pixels (after majority filter application; before after-processing it was 49.4%). The distribution of particular LCZ types in the two classification schemes was broadly similar, especially for LCZs 2, 4, 6, 8, 9, A and C (Fig. 7), while it varied considerably for LCZs 3, 5, 10, and E (Fig. 6).

3.3 Evaluation of the spatial distribution of local climate zones

As a result of using an objective method for the delineation of compact urban development (Halás et al., 2012), it was possible to compare not only the absolute area of each LCZ in the surveyed cities, but also the relative share of each LCZ type in each of the studied cities.

Table 4 shows that Brno is by an order of magnitude larger in terms of its absolute size than Hradec Králové and Olomouc. When the relative values of Brno were compared with those of Hradec Králové and Olomouc, the higher size category of Brno manifested itself in the presence of fragments of LCZ 1 and a slightly higher percentage of LCZ 2. On the other hand, the percentage of LCZ 5 suggests that the city of Olomouc was historically in the same size category as Brno. The smaller extent of LCZ 5 in Hradec Králové corresponds to the fact that until the 1950s, the city belonged in a lower size category. Given its different morphological structure (a smaller urban centre and gradual absorption of the surrounding communities with preserved low-rise developments), Hradec Králové had by far the highest relative share of LCZ 6 and also a slightly higher relative share of LCZ 9 (Tab. 4).

In the historic centres of all three cities, LCZ 2 dominated in the form of a small number of compact areas placed close to one another. In Brno and Olomouc, compact areas of LCZ 5 were formed in the neighbourhood of city centres (in Olomouc

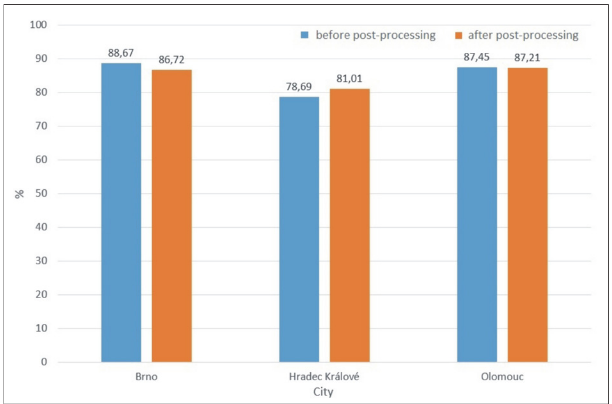

Fig. 6: Classification performance – percentage of pixels classified into LCZ classes in agreement with expert knowledge as overall producer accuracy before and after post-processing. Source: authors' elaboration

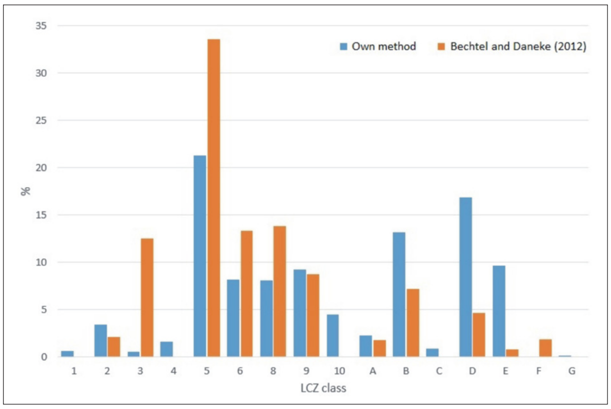

Fig. 7: Comparison of LCZ percentage in the compact development area of Brno with the methods presented here and with the method of Bechtel and Daneke (2012) Source: authors' elaboration

	1	2	3	4	5	6	8	9	10	A	B	C	D	E	F	G	SUM
Brno	48	277	44	132	1,761	675	666	758	367	182	1,086	70	1,395	796	0	9	8,266
	(0.6)	(3.4)	(0.5)	(1.6)	(21.3)	(8.2)	(8.1)	(9.2)	(4.4)	(2.2)	(13.1)	(0.8)	(16.9)	(9.6)	(0.0)	(0.1)	(100.0)
Olomouc	3	60	2	51	845	134	144	367	150	11	261	21	721	173	5	6	2,954
	(0.1)	(2.0)	(0.1)	(1.7)	(28.6)	(4.5)	(4.9)	(12.4)	(5.1)	(0.4)	(8.8)	(0.7)	(24.4)	(5.9)	(0.2)	(0.2)	(100.0)
Hradec Králové	0	67	25	23	305	606	234	409	27	59	351	0	605	106	0	18	2,835
	(0.0)	(2.4)	(0.9)	(0.8)	(10.8)	(21.4)	(8.3)	(14.4)	(1.0)	(2.1)	(12.4)	(0.0)	(21.3)	(3.7)	(0.0)	(0.6)	(100.0)

Tab. 4: The absolute area of each LCZ in compact urban development [in hectares (in %)]
Source: authors' elaboration

they were separated from the city centre by urban parks – LCZ B), while in Hradec Králové such large compact areas of LZC 5 were formed in the inner part of the city. In Hradec Králové, the fragments of LCZ 5 alternated with LCZ 6 without any signs of concentric layout. In all three cities, larger areas of LCZ 8 and LCZ 10 were concentrated along the perimeters of the inner cities or shaped as characteristic projections of compact development into the surrounding countryside. Particularly in Brno, vast LCZ 8 areas were located beyond the compact urban development. Compared with the other two cities, Brno showed a larger percentage of LCZ E, which related to its status as a city of international significance – large industrial areas (railway yards, car parks), traffic junctions, and the Brno Exhibition Centre.

In Brno, the compact urban development was surrounded on three sides by a narrow strip of LCZ B (allotments and orchards), followed by a mosaic of forests (LCZ A) and fields (LCZ D). Only in the south and southeast did the compact urban development merge into a purely agricultural landscape of fields (LCZ D). In Hradec Králové and Olomouc, the "ring" of LCZ B between the compact urban development and the surrounding landscape did not display so strong a contrast as in Brno. In the majority of peripheries in these cities, the compact urban development turned sharply into farmland with fields (LCZ D); only in the southwest of Hradec Králové did the compact urban development border on a vast wooded area (LCZ A).

From the perspective of studying local climates, it is also important to evaluate the share of LCZ classes in rural settlements. It turned out that each municipality (village) in the surveyed region has formed at least one site of the LCZ of built types classes (LCZbt). Specifically, LCZ 9 dominated in rural municipalities, with fragments of LCZ 6 in the central parts of these settlements. Some small areas of LCZ 5 (relevant at a local level) appeared in larger municipalities or municipalities with historical buildings (see Fig. 5).

4. Discussion

Our work highlights a GIS-based approach and its advantages in the delineation of LCZs in terms of the standardisation and objectification of the classification procedures. The main disadvantages of GIS-based approaches are differences in the quality and accessibility of input data between cities and high time demands. These may be minimised by developing uniform sources of input data in the future (e.g. Fritz et al., 2012). On the other hand, satellite image-based methods have been considered faster so far, easier to use, widely available and therefore representing a seemingly more progressive solution. Bechtel et al. (2015) even provide a freely available tool for defining LCZs in the SAGA-GIS program. The satellite image-based methods, however, suffer from the non-standardised (subjective) delineation of the training area (training pixels). At the same time, we have demonstrated that the method used for classification (or even of the setting of one particular method) could significantly influence the results. Therefore, the future development of GIS-based methods may play an important role in efforts to reach a universal LCZ classification method (i.e. as a tool for the delineation of LCZs in the area of training pixels for the image-based methods). Gál et al. (2015) have already presented some advantages of an approach using combined methods for LCZ classification. To develop a universal classification algorithm, however, it will be necessary to research a wide sample of world urban morphologies, to find data sources from which parameters can be derived in most world regions, and to be precise about the setting of the parameters of the decision-making algorithm and optimal pixel size as the carriers of spatial information entering the classification process (the data sources and the algorithm used in this particular study are, for example, only applicable to Central Europe, specifically to the Czech Republic).

When mapping the local climate zones in this study, we met up with some specific features of the Central European area, which had already been tackled by researchers such as Bechtel and Daneke (2012), Lelovics et al. (2014), Lehnert et al. (2015), and Przybylak et al. (2015). Therefore, because of these regionally-specific features, borders of the intervals of the physical properties of LCZ 4 and LCZ 5 had to be slightly modified, as compared to those suggested by Stewart and Oke (2012). In this context, only the definition of LCZ 10 seemed to be a serious conceptual problem and the way in which it can be delineated appropriately must be discussed further. A major outstanding methodological question, however, continues to exist in the need for the adjustment of the intervals of the physical properties of the environment (whether to keep the original designation of the parent class in a standard set of LCZs and point out the differences, indicate the subclass or, on the basis of research in other regions of the world, stimulate discussion on a revision of the proposed typical values of geometric and surface cover properties of the parent class).

The results of previous studies broadly confirm the relevance of LCZs at the level of the local climate (Houet and Pigeon, 2011; Stewart et al., 2013; Fenner et al., 2014, Lelovics et al., 2014; Lehnert et al., 2015; Alexander et al., 2015; Skarbit et al., 2015). Nevertheless, a question has arisen recently about the intra-zonal variability of LCZs, i.e. about the extent to which the local climate of the area of a particular zone is affected by the geometrical structure of buildings (Bechtel and Daneke, 2012; Lehnert et al., 2015), its size and position in relation to other climatic zones (Lindén et al., 2015; Leconte et al., 2015), or the impacts of the landscape relief on the behaviour of the climate zones (Bokwa et al., 2015). All of these relationships may be analysed more accurately as a result of knowledge of the spatial pattern of the distribution of LCZs in Brno, Hradec Králové, or Olomouc and their surroundings.

5. Conclusion

Using case studies from the Central European area, we have managed to design a GIS-based method for mapping LCZs based on the physical parameters of the environment and a clearly defined decision-making algorithm. The method presented here showed good performance and can be transferred between Central European cities (provided the required input data are available). Our analysis shows that the decision-making algorithm for defining the percentage coverage for individual LCZs was in good agreement with areas defined on the basis of expert-based knowledge, and the results were broadly similar to results obtained with the satellite image-based method developed by Bechtel and Daneke (2012). The differences that existed, however, emphasized the necessity for the further standardisation and objectification of the classification process and the delineation of individual areas of LCZs.

Central European cities show a similar spatial pattern of the occurrence of areas of individual LCZ classes. LCZ 2 dominates the central parts of cities, LCZ 5 areas prevail with the fragments of LCZ 6, which spread from the external city centre borders up to the edge of the compact urban development, and LCZ 8 and 10 produce projections of compact development into the surrounding countryside. The character of rural municipalities in the Central European region gives rise to the formation of the LCZ built type (LCZ_{bt}) even beyond the city borders. These findings and the very possibility of the clearly-defined delineation of LCZ areas may lead to significant advances in the further study of urban climates in Central European cities. For an upcoming sequel to this study, a thorough analysis of LCZ areas in Brno, Hradec Králové, and Olomouc and their surroundings with respect to their climatological characteristics will be carried out.

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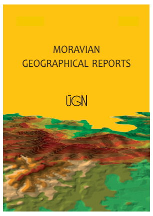

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Biogeomorphological effects of leaf accumulations in stepped-bed channels: Exploratory study, Moravskoslezské Beskydy Mountains, Czech Republic

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Abstract

The stepped-bed system, with a step-like longitudinal profile, is typical morphology in steep headwater streams. These systems are created by a series of coarse sediments or instream wood (steps with supercritical flows) interspaced with finer material (forming pools with subcritical flows). In the case of well-developed steps and pools, the resulting channel-reach morphology is referred to as "step-pool" morphology. In this study, we identify a previously undescribed type of step-pool formation, the "foliaged step-pool", in the high-gradient Stoligy Stream of the Moravskoslezské Beskydy Mountains. The defining feature of this formation is the significant presence of leaves in the step structure. The geometry of the steps and pools was measured and the parameters that characterise the distribution, amount and function of leaves acting in these areas were defined. Statistical results showed differences between non-foliaged and foliaged step-pool formations, in which the latter showed a significant increase in storage level, influencing the channel's hydrodynamics. Particle-size analyses demonstrated that foliaged step-pool formations had finer sediment in the pools, which indicates that there are differences in sediment transport processes between foliaged and non-foliaged formations. These results offer new insights into stepped-bed and step-pool morphology, providing directions for further research on small streams in deciduous forested regions.

Key words: *mountain streams, foliaged step-pool, leaf accumulation, instream wood, Moravskoslezské Beskydy Mts., Czech Republic*

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1. Introduction

Fluvial systems are influenced to varying degrees by living organisms and their dead remains. This is exemplified by the impact of trees on river channels. Living trees armour channel banks with their roots, decreasing the rate of lateral erosion and the possibility of activating bank failures or landslides. Similarly, vegetation on channel benches reinforces sediments, making these forms more stable during flood events. The interception ability of trees significantly decreases the total amount of water delivery into fluvial systems. Instream wood fragments also directly affect river systems. Large wood pieces (LW) include a variety of coarse woody material (such as logs, branches, stumps and roots) that are ≥ 0.1 m in diameter and usually at least 0.5–1 m in length; these generally originate when trees and shrubs fall apart and the pieces are delivered into channels (Máčka and Krejčí, 2010). LW-created structures (e.g. steps and pools) retain sediment and increase the bed roughness, bankfull depth and mean particle size; they also reduce sediment transport relative to reaches that lack LW (Bilby and Ward, 1989; Curran and Wohl, 2003; Faustini and Jones, 2003; Gomi et al., 2003; Wilcox and Wohl, 2006; Burrows et al., 2012; Scott et al., 2014). LW accumulations decrease the probability of bed particle movement during high flows and reduce the mean travel distance of entrained particles, thus reducing sediment transport efficiency (Faustini and Jones, 2003). Small wood pieces (SW) are defined as woody particles (such as logs, branches and roots) that are ≤ 0.1 m in diameter. Wallace et al. (2000, 2001) and Burrows et al. (2012) documented that SW can have an important effect on channel processes in narrow headwaters with lower discharges.

Leaf litter can also affect the channels of small mountain streams independently of SW or LW. Although the field of fluvial geomorphology has expanded in the past two decades to include greater knowledge of channel-reach

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morphology and processes related to high gradient streams, the influence of leaf litter is poorly characterised. Interdisciplinary research on the effects of leaf litter has usually described results from a hydrobiological point of view or it has focused on transport dynamics; however, the distribution of leaf patches is one of the main aims of leaf research (Richardson, 1992; Pretty and Dobson, 2004; Hoover et al., 2006; Kochi et al., 2009). Terrestrially-derived leaf litter is a critical resource in many small streams, providing food and habitat for decomposers, detritivores and macroinvertebrates (Richardson, 1992). Hoover et al. (2006) described the principles of movement and deposition of leaves in pool-riffle channel-reach systems. They concluded that flow velocity and the presence of coarse sediments in the channel were the main factors influencing mean transport velocity and the distance over which leaves were deposited. Leaf transport distances were 2.6 times greater in riffle units than in pool channel units; the leaves also had a higher transport velocity. Kochi et al. (2009) investigated the differences between green leaves (from the current year) and senescent leaves (from previous years). Senescent leaves were retained in greater numbers on large wood pieces and in backwaters than were green leaves, which were usually trapped by cobbles. Both studies noted that floating leaves were stored more frequently when the grain-size parameters of the channel bed increased.

All species of deciduous trees are potential sources of leaf litter; in our study area, the predominant trees were beech and maple (*Fagus sylvatica* and *Acer pseudoplatanus*). Larger leaves, however, have higher potential to be deposited on obstacles in the stream channel (Kochi et al., 2009). Once leaves reach the channel, they become an integral part of the fluvial system and they are stored or transported downstream by flowing water (Hoover et al., 2006). The amount of organic matter stored in a streambed depends on climate, stream order and retention structures in the streambed (Hoover et al., 2006). The discharge and stream velocity necessary for effective transport of leaves is less than for bedload transport of solid particles. Thus, leaves are transported during much lower flow events, meaning that the morphology of foliaged forms has high temporal dynamics. During transport, organic matter may be retained by structures in the streambed such as woody debris and cobbles, or by backwaters behind obstacles (Kochi et al., 2009). Deposition of leaves is usually realised in contact zones with obstacles, and typically occurs on larger boulders or LW (Hoover et al., 2006). Transported leaves gradually accumulate and cover boulders or SW/LW steps, creating "foliaged forms" (Fig. 1). An armoured isolation layer of leaves develops due to mutual adhesion between wet leaves. This layer is practically waterproof and concentrates the direction of water flow into single points on a step (Přibyla and Hradecký, 2009). Leaves accumulated over the long-term gradually subside; the total height of steps decreases and leaves lose their isolation characteristics as anaerobic biologic decomposition occurs (Kochi et al., 2009). A higher amount of leaves is observed in the steps of step-pool systems, whereas in pool-riffle reaches, leaves tend to be stored in pools (Hoover et al., 2006).

Fig. 1: Leaf accumulations (litter patches) on large boulders. Photo: Z. Přibyla

The goal of this study is to evaluate the influence of leaves on the geometric parameters, grain-size characteristics and stability of bedforms in steep headwater channels with cascade and step-pool channel-reach morphologies. Cascades and step-pools generally occur over a wide range of steep channel gradients, which usually exceed 0.04 m/m in confined valleys; they are characterised by longitudinally and laterally disorganised bed material that typically consists of gravels, cobbles and boulders (Montogomery and Buffington, 1997). Alternation between coarser sediments in the steps and finer sediments in the pools gives rise to a staircase-like longitudinal profile (Chin, 2002). The steps usually consist of relatively large, immobile boulders with a random spatial distribution in the channel. Smaller cobbles accumulate around the large boulders creating stable steps. Pools form downstream of the steps due to the scouring action of water off the crest of the steps. The pools contain relatively finer gravel and sand, and this material is transported more often (several times per year). Pool depth is controlled by the step height and discharge regime (Comiti et al., 2005). Montgomery and Buffington (1997) distinguished cascade and step-pool morphology by the length of the pools, defining cascade reach as having pools with a shorter length than bankfull channel width. Comiti and Mao (2012) characterised cascades and step-pools as part of a stepped-bed morphology within the channel-reach system. For poorly-developed significant steps and pools, the channel-reach morphology is referred to as "plane bed" or "rapid", *sensu* Montgomery and Buffington (1997) and Zimmermann and Church (2001).

Three of the most important and commonly-studied geomorphic variables of step-pool channels are the step height, wavelength and channel slope (Zimmermann and Church, 2001). Another important parameter is the step steepness (H/L). Step-pools evolve towards a condition of maximum flow resistance that implies maximum stability (Abrahams et al., 1995). Flow resistance can be conceived of as the influence of bed roughness on flow velocity. The higher the bed roughness, the less potential energy is available for sediment transport because the mean flow velocity is slowed. Both flume experiments and field measurements show that maximum flow resistance is achieved when the steps are regularly spaced and the mean step steepness H/L (step height/step length) is slightly greater than the channel slope S, where $1 \leq H/L/S \leq 2$. This morphology thus represents an equilibrium form adjusted by the flow regime, particle size and slope (Abrahams and Atkinson, 1995; Chin and Wohl, 2005).

This study presents an introduction to the concept of foliaged channel bedforms. Our main objectives are to recognise the fundamental influence of leaves on bedforms, to describe the composition of foliage bedforms, to evaluate various morphometric quantitative parameters and to describe the origin, evolution and function of foliaged bedforms.

We investigate the following questions:

1. Are there significant differences in basic geometric parameters (H, L, W) between foliaged and unfoliaged step-pool formations?
2. Is there a difference in the grain-size parameters of foliaged step-pools compared to step-pools without leaves?
3. Can the presence of leaves condition the occurrence of step-pool formations?
4. Is the observed increase in step permeability due to the presence of leaves? and
5. How we can determine the stability of foliaged formations? What magnitude of discharge leads to removal of leaves from foliaged steps?

2. Studied stream

The Stoligy Stream was used as a reference stream in this study. The stream is located in the eastern part of the Moravskoslezské Beskydy Mts. in the Western Carpathian Flysch Belt (Fig. 2), and it is a left-side tributary of the Lomná Stream. The total length of the studied channel-reach is 160 m and the channel-reach begins at an altitude of 608 m a.s.l. The watershed area above the studied reach is 0.26 km^2 and the mean channel gradient is 0.14 m/m. The valley bottom has a gully-like character; the stream is incised into the transport and accumulative zone of a Pleistocene landslide, and active development of the banks has resulted in high delivery of fine claystone sediments from bank failures. The typical channel-reach morphology is step-pool, occasionally alternating with cascades and rapids.

The studied watershed is underlain by flysch rocks of the Godula Member. Alternating layers of resistant sandstone and soft claystone predispose the area to both deep and shallow landslide activity (e.g. Hradecký and Pánek, 2008; Pánek et al., 2011). The grain-size parameters of the bed sediments (d_{50}, d_{90}) are generally lower in flysch-based streams than in streams in other geological settings. In spite of this fact, very low critical condition values were obtained for bedload transport of certain grain-size fractions in local headwater channels (Galia et al., 2015). In addition, the local streams are prone to accelerated erosional processes when low sediment volumes are available for fluvial transport (Galia and Škarpich, 2013; Škarpich et al., 2013).

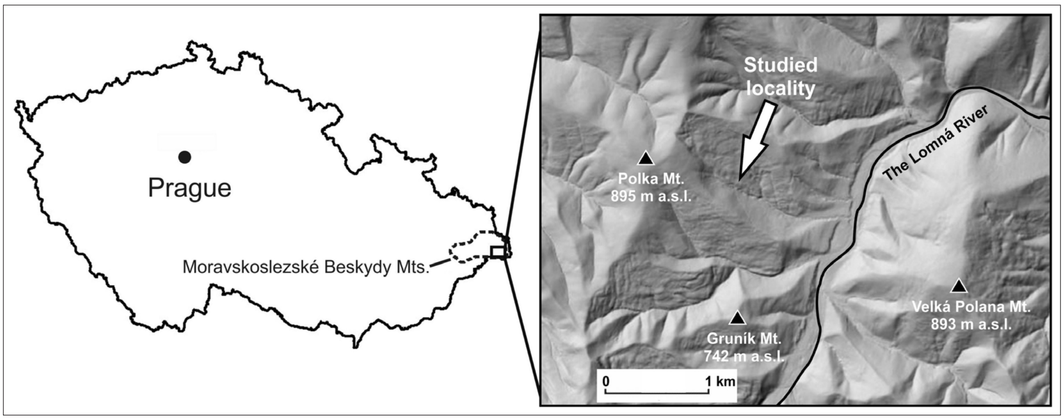

Fig. 2: Location of the studied stream. Source: State Administration of Land and Cadastre; authors' elaboration

The studied watershed is covered by an agricultural forest dominated by beech (*Fagus sylvatica*), which is the main source of leaf litter in the channels. Maple (*Acer pseudoplatanus*) also occurs in the study area. The natural character of the gullies and the stepped morphology of the channels form a biotope suitable for a variety of amphibians (e.g. *Rana temporaria* and *Salamandra salamandra*) and invertebrate aquatic animals. Small wood pieces were the dominant type of woody material present in the studied channel; thus, we later refer to the steps created by woody material as SW steps. Occurrence of LW in the studied channel was uncommon because of intensive local forest management, which includes removal of logs from the channel.

3. Methods

Leaf accumulations (an equivalent is "leaf litter patches", *sensu* Hoover et al., 2006; Kochi et al., 2009) refer to clusters of leaves that accumulate in channels because of obstacles (e.g. individual boulders, boulder steps or in-stream wood). Leaf accumulations on certain channel units such as steps can be referred to as "leaf formations" (e.g. leaf accumulations on the step). The step-pool formations (SPs) identified in this study were classified into groups based on their origin and rate of foliage F (Fig. 3).

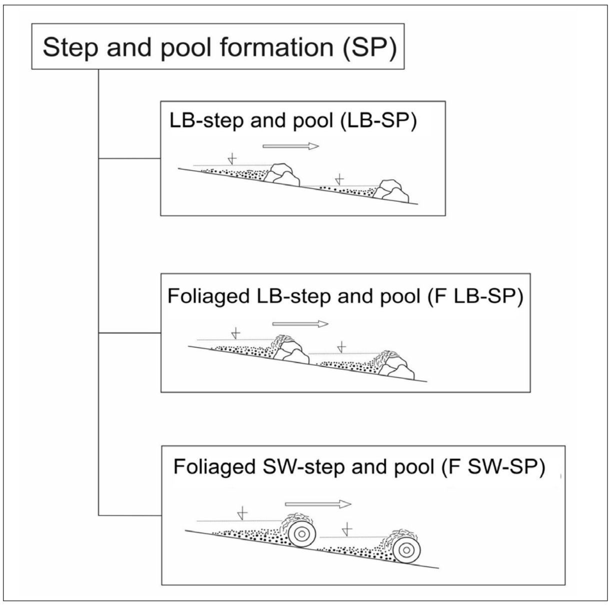

Fig. 3: Types of step-pool formations in the study area. SP is an unfoliaged step-pool formation, F LB-SP is a foliaged large boulder step-pool, and F SW-SP is a foliaged small wood step-pool. Source: authors' conceptualisation

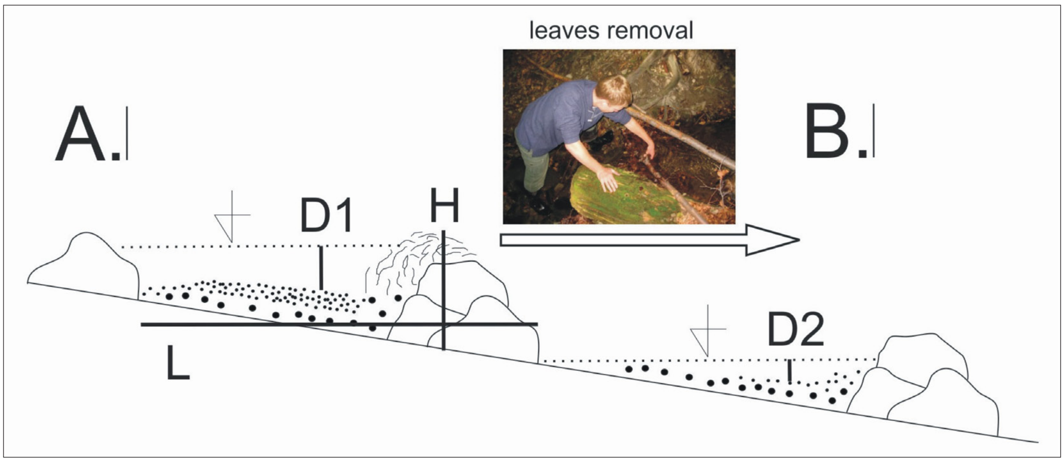

Fig. 4: Measurement of step-pool parameters. A.: measurements of H (height), L (length) and D1 (pool depth); B.: measurements after leaf removal, including D2 (pool depth without leaves). Source: authors' conceptualisation

Parameter	Label	Unit	Description
Height of step	*H*	m	see Fig. 4
Wavelength (distance between two steps)	*L*	m	see Fig. 4
Pool width	*W*	m	Pool width measured in the first third length of pool
Foliage	*F*	%	Area covered by leaves on boulder step or SW step
Flow concentration	*fC*	%	Percentage of scouring water width on a total width of step
Depth with leaf	*D1*	mm	Pool depth measured in the first third length of pool
Depth after leaf removal	*D2*	mm	Pool depth measured in the same point after removal of leaves on step
Foliage depth	*fD*	mm	*D1* – *D2*
Relative foliaged depth	*fD%*	%	Percentage of the foliage depth on the total pool depth (*fD%* = *fD* / *D1* × 100)

Tab. 1: Measured parameters of the step-pool formations. Source: authors' elaboration

The geometry of the step-pools – namely the step height (*H*), wavelength (*L*) and channel width (*W*) – was measured in foliaged and unfoliaged step-pools (Fig. 4). The methodology we used differed from the commonly-used approaches because pools including foliage formations are directly influenced by the characteristics of the downstream steps. In common alluvial SPs, the geometry of pools is usually determined by water drops from upstream steps (e.g. Zimmermann, Church, 2001).

It was necessary to establish a descriptive terminology for foliaged SPs because the literature currently lacks this terminology; this allowed us to define quantifiable parameters that described the sorting and amount of leaves that accumulate in the step-pool systems (Tab. 1). These parameters describe the influence of leaves on the origin and function of the step-pools. Foliage (*F*) denotes the percentage area of an obstruction (e.g. a boulder step or in-stream wood) covered by accumulated leaves. We used *F* as a distinguishing factor to determine whether an SP was foliaged or not; an SP was considered foliaged when $F \geq 10\%$ and leaves were involved with filling the pores between individual boulders or pieces of instream wood. In other words, the presence of leaves could affect the water level in a pool. The flow concentration (*fC*) indicates the percentage ratio of the concentration of water scour from steps during ordinary flow. Thus, *fC* represents the ratio between the step width and the concentrated water flow on the crest of a step. This parameter was also affected by the amount of leaves on a step for foliaged SPs (Fig. 5). *D1* denotes pool depth in SPs, while *D2* is the pool depth after careful removal of leaves

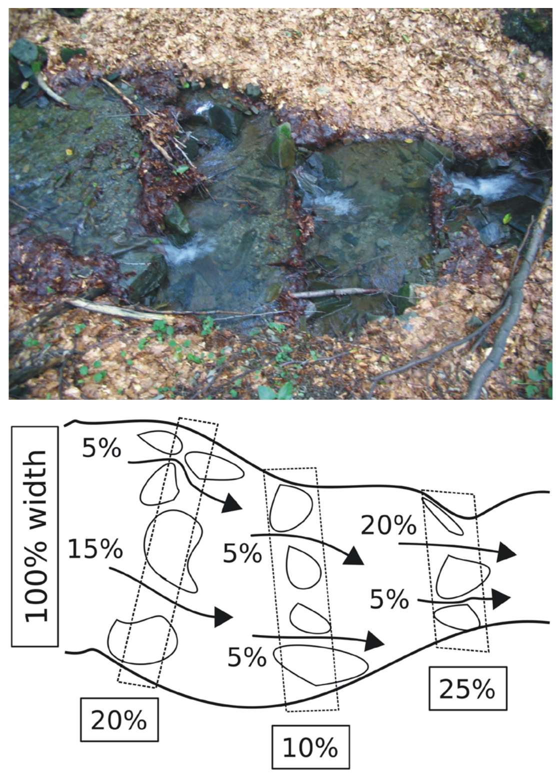

Fig. 5: Description of the parameter flow concentration fC Source: authors' elaboration

from a step, ensuring that the structure of the step was preserved. Both $D1$ and $D2$ were measured at the same point, one third of the pool length halfway through the channel cross-section. The variance in depth ($D1 – D2$) is defined as the foliage depth fD. This parameter represents the height of water affected by the presence of leaf accumulations on a step; it can be applied when retention of water in the foliaged SPs is considered. Relative foliaged depth ($fD\%$) denotes the percentage ratio of foliaged pool depth to pool depth after leaf removal: $fD\% = fD / D1 \times 100$. A correlation matrix was used to find the relationships between all parameters and calculate p statistics.

A standardised measuring template was used to measure the five largest boulders in every step. Fine sediments were taken from pools of foliaged ($n = 4$) and unfoliaged SPs ($n = 3$) in August of 2008. Sieving analysis was performed using a Fritsch sieving aperture and the data were evaluated using Gradistat, a freely available extension of Microsoft Excel.

4. Results

4.1 Geometric parameters of the step-pools

Table 2 shows the mean values of the evaluated parameters for individual types of SPs. Foliaged SPs have notably larger geometric parameter values (H, L, W) than unfoliaged formations. The correlation matrix between the LB-SP, F LB-SP and F SW-SP variables showed a variety of relationships. Comparing the correlations between individual geometric parameters (H, L, and W) showed that the strongest correlation occurred in the LB-SP set. In general, their proportions were strictly related to the channel gradient, discharge and grain-size parameters (Tab. 3). Only the L vs. W linear relationship, however, was statistically significant at $\alpha = 0.05$ because of the low number (n = 9) of observations. There were lower correlations between geometric parameters for F LB-SPs (Tab. 4), where leaves had an influence on SPs. The F SW-SP formations showed very little correlation (Tab. 5), suggesting that SW and leaf litter led to the formation of SPs and traditional morphogenetic factors (channel gradient, discharge, and particle size) only had a weak influence; the occurrence of SW was the leading factor. The step height increased with size of the largest boulders in the steps for both unfoliaged ($r = 0.66$) and foliaged SPs ($r = 0.39$). Thus, the step height was directly related to size of key boulders in the steps and not to the amount of leaves in the steps.

The depth $D1$ had a positive correlation ($r = 0.47–0.54$) with the step height H in all types of observed step-pool formations, probably because pool depth is controlled by water scour from the upstream step in step-pool channels (Lenzi and Comiti, 2003). In addition, $D1$ correlated strongly with $D2$ for F LB-SPs and F SW-SPs. Thus, the pool depth is related to various step parameters prior to its foliation. The depth $D2$ was significantly lower in foliaged formations than the $D1$ pool depths in unfoliaged SPs, suggesting that leaf litter increased pool retention. Considering the pool geometry, there was a good but not statistically significant correlation between the pool depth $D1$ or $D2$ with W for the group of non-foliaged LB-SPs.

Foliation (F) had no correlation with the step height and only a poor correlation with L and W. There was a strong negative relationship between foliation (r was − 0.42 for F LB-SPs and − 0.70 for F SW-SPs) and the concentration of flow on the steps (fC). Thus, a decrease in fC was associated with an increase in step foliation. Foliation also correlated with the foliaged depth ($fD\%$), showing that increasing step foliation caused an increase in foliaged depth. The observed correlation was stronger for the F SW-SP group than the F LB-SP group and foliation usually reached higher values in the F SW-SP group (76%) than in the F LB-SP group (57%). A similar trend was described by Kochi et al. (2009), who found that senescent leaves accumulated in higher volumes on LW steps than on boulder steps (in a ratio of 60:40). The concentration of flow on the step (fC) indicated that there was a strong negative correlation with step height and

Parameter	All SP	Unfoliaged SP (LB-SP)	Foliaged SP	Foliaged large boulder-SP (F LB-SP)	Foliaged small wood-SP (F SW-SP)
Number of SP (n)	59	9	50	29	21
H (m)	0.29	0.22	0.30	0.31	0.28
L (m)	1.32	1.09	1.36	1.38	1.33
W (m)	1.09	1.03	1.11	1.05	1.19
H/L	0.23	0.21	0.24	0.24	0.23
$H/L/S$	1.66	1.52	1.71	1.71	1.64
L/W	1.24	1.07	1.28	1.33	1.18
$D1$ (mm)	99	96	100	101	98
$D2$ (mm)	-	-	68	77	56
fD (mm)	-	-	32	24	42
$fD\%$ (%)	-	-	33.4	25.7	44.1
F (%)	-	-	65.1	57.1	76.2
fC (%)	34.4	45.6	32.4	34.5	29.5
d_{50} step (mm)	108	123	105	105	-
d_{50} pool (mm)	5.5	5.9	5.2	5.2	5.2

Tab. 2: Means of measured parameters of the step-pool formations. For notation please see Table 1
Source: authors' calculations

pool depth for the LB-SP group. Thus, the concentration of flow is exclusively controlled by the step height and the boulder size. This is in contrast with foliaged forms, where the concentration was dependent on the amount of leaves on the steps.

Generally, these results show that foliaged SW step-pool formations had lower correlations with the geometric parameters of the channels; their measured parameters also varied more. The supply of SW to channels is random, so the presence of steps does not reflect local conditions such as the channel gradient, bankfull parameters or grain-size parameters. Foliaged SW step-pools are more likely to be influenced by leaf litter. Unfoliaged LB-SPs and foliaged LB-SPs are more likely to have local parameters that predispose them towards stepped-bed morphology.

4.2 Retention potential of foliaged step-pool formations

The parameter that most reflected the influence of leaf litter on channel bedforms was the relative foliaged depth (*fD%*). We suggest that the presence of leaves in bedforms, which is expressed by an increase in *fD%*, has a strong effect on step impermeability, grain size parameters of the pools, flow velocity at the step and in the pool and bedform stability. We observed a rapid decrease in pool depth (*D*2) and the immediate transport of bed material such as finer sediment, small twigs and accumulated leaves from the pool during leaf removal from the steps.

The mean value of the relative foliaged depth in Stoligy Stream was 33.4% (*fD* = 32 mm). A large difference was observed between foliaged large boulder step-pools and foliaged SW step-pools, which respectively had *fD%* values of 22.8% (*fD* = 23 mm) and 41.8% (*fD* = 41 mm). We note that the foliaged depth did not change after removal of leaves in the nine cases of the F LB-SP group. This observation implies that leaf accumulations have a greater influence on the morphometric parameters of woody debris steps than on boulder steps.

4.3 Evolution of foliaged step-pool formations

We observed mutual spatial storage of leaves and fine sediments during removal of leaves from foliaged steps. We distinguished two special cases of foliaged steps and pools (Fig. 6). Type *A* represents the foliaged LB-SP sequence, which generally originated because of the accumulation of leaves on steps (Fig. 6A). In this sequence, an originally rapid channel reach gradually shifted towards a step-

n = 9	*H*	*L*	*W*	*fC*	*D*1
H	**1**				
L	0.39	**1**			
W	0.60	**0.88**	**1**		
fC	– 0.48	0.03	– 0.13	**1**	
*D*1	0.49	0.42	0.60	0.15	**1**

Tab. 3: Correlation matrix for LB SPs with related p-values. Significant correlations at the 0.05 level are denoted in bold letters. For notation please see Table 1
Source: authors' elaboration

n = 29	*H*	*L*	*W*	*fC*	*F*	*D*1	*D*2	*fD*	*fD%*
H	**1**								
L	**0.44**	**1**							
W	0.35	**0.57**	**1**						
fC	0.09	**– 0.43**	– 0.10	**1**					
F	0.09	**0.37**	0.03	**– 0.42**	**1**				
*D*1	**0.47**	0.17	0.26	–-0.05	– 0.16	**1**			
*D*2	**0.37**	– 0.04	0.27	0.20	**– 0.45**	**0.88**	**1**		
fD	0.13	**0.41**	– 0.07	**– 0.51**	**0.64**	0.09	**– 0.39**	**1**	
fD%	0.12	0.29	– 0.15	**– 0.39**	**0.71**	– 0.22	**– 0.62**	**0.88**	**1**

Tab. 4: Correlation matrix for foliaged LB SPs with related p-values. Significant correlations at the 0.05 level are denoted in bold letters. For notation please see Table 1. Source: authors' elaboration

n = 29	*H*	*L*	*W*	*fC*	*F*	*D*1	*D*2	*fD*	*fD%*
H	**1**								
L	0.33	**1**							
W	– 0.17	0.22	**1**						
fC	0.13	– 0.11	– 0.24	**1**					
F	– 0.11	0.25	0.24	**– 0.70**	**1**				
*D*1	**0.54**	– 0.09	– 0.19	0.15	– 0.06	**1**			
*D*2	**0.49**	– 0.16	– 0.12	0.51	**– 0.45**	**0.80**	**1**		
fD	0.13	0.09	– 0.12	**– 0.53**	**0.58**	0.41	– 0.23	**1**	
fD%	0.16	0.32	– 0.10	**– 0.46**	**0.68**	– 0.12	**– 0.60**	**0.71**	**1**

Tab. 5: Correlation matrix for foliaged SW SPs with related p-values. Significant correlations at the 0.05 level are denoted in bold letters. Source: authors' elaboration

pool morphology because of the presence of leaves in the channel. Development of this formation begins when leaves transported by the stream begin to deposit. Later deposition of leaves on large clusters of coarse sediment increases the retention capacity of the cluster. A step is created as the spaces between individual boulders are plugged by leaves. Fine sediments begin to deposit in the pool, partly covering the foliaged step. If leaves are removed from the step, most of the material in the pool is transported downstream, the step-pool sequence gradually disappears and the channel-reach morphology is transformed from step-pool back to a rapid nature. Thus, the occurrence of leaves in a channel is the main factor that gives rise to such step-pool morphology. The same situation can arise for SW/LW rather than boulders (Fig. 6B and 6C.) Type *B* foliaged steps and pools shift from a step-pool to a rapid channel reach morphology after removal of leaves in the case, when the SW/LW is not fully spanning the channel under the level of annual discharge. In contrast, type *C*, which includes the so-called hanging SPs, differs significantly from type *B* because of the position of logs. In Type *C*, the SW/LW is located above the level of annual discharge, allowing leaves to be transported below this obstruction. A step can only be created when the water level reaches the position of the log during higher discharges. In that case, fine woody debris and leaves fill the space between the channel bed and the log to create a step and pool sequence. Consequently, the pool is then filled by fine sediment, rapid morphology develops after removal of leaves.

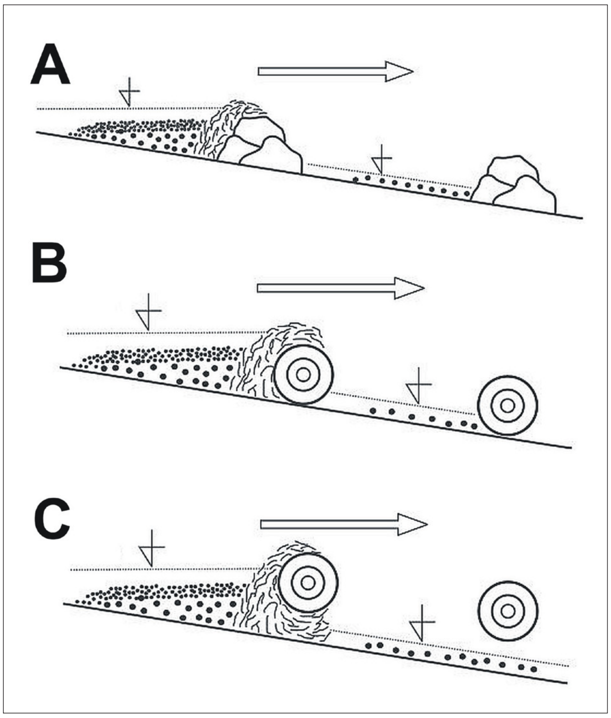

Fig. 6: Different origin of foliaged steps: A – step is created by a group of a few large boulders; B – step is formed by a piece of wood on the channel bottom; and C – step is the result of fallen wood over the channel
Source: authors' conceptualisation

We note that removal of leaves caused many step-pool formations to wash out; in total, 60% of the originally foliaged SW-SPs and 25% of the LB-SPs were destroyed. These channel reaches were transformed back to rapid reaches or cascades at higher channel gradients (Fig. 7). This result implies that 40% of all step-pool formations transitioned to this morphology because of the presence of leaves in the active channel.

5. Discussion

5.1 Foliaged step-pool formation geometry

Our results show that the geometry of foliaged SW-SPs was controlled by the presence of leaf litter. The geometry of the foliaged LB-SP groups reflects other predispositions of stepped-bed morphology (such as the channel gradient

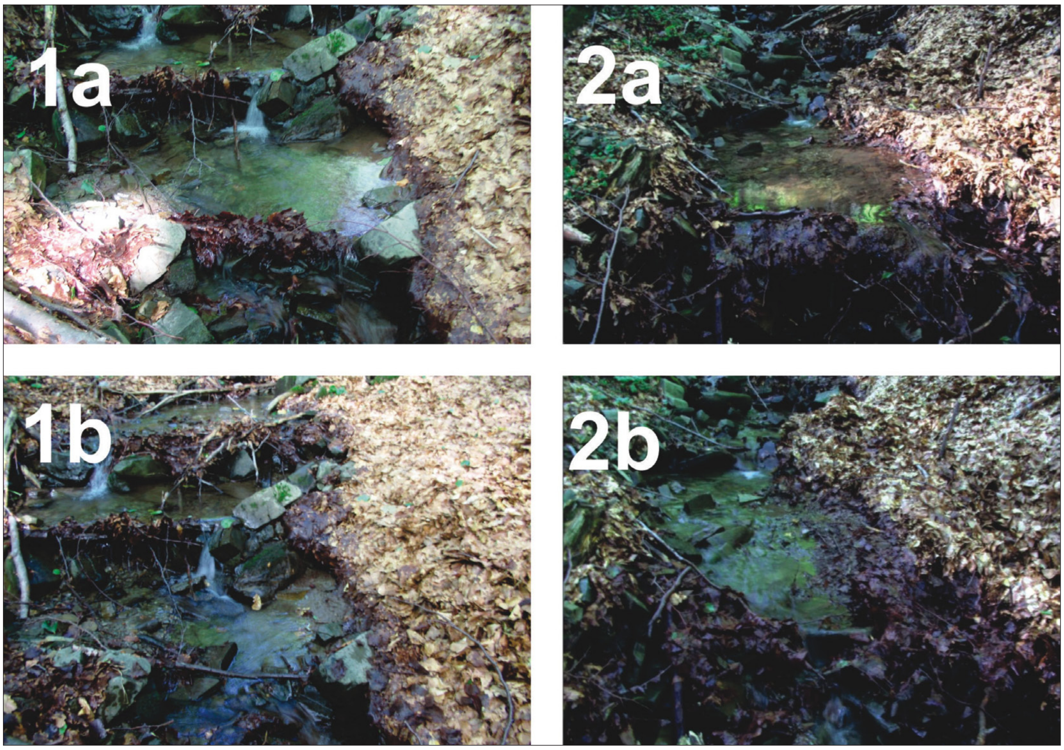

Fig. 7: A change in foliage depth before (a) and after (b) leaf removal, showing significant lowering of the water level. Both figures show steps created by small wood pieces. Source: authors' photographs

and presence of boulders). There are, however, no previous studies of foliaged stepped-bed morphology that can confirm this conclusion. One exception is the work of Borák (2012) from steep headwater streams. We also compared the geometric characteristics of foliaged step-pools with alluvial (Chin, 1999; Chartrand and Whiting, 2000; Lenzi, 2001; Nickolotsky and Pawlowsky, 2007; Recking et al., 2012; Frandofer and Lehotský, 2013) and bedrock (Duckson and Duckson, 2001) step-pool morphologies that occurred in areas similar to our study location, with small watersheds and steep channel gradients. Borák (2012) investigated foliaged step-pool systems in the flysch-based high-gradient Mazák Stream ($A = 0.9$ km^2) in the Western Carpathians, where the mean bankfull width was 1.08 m and the channel gradient was 0.24 m/m. He calculated a significantly lower value for the $H/L/S$ relationship (1.05) than we found for the Stoligy step-pools (1.71). The difference is likely due to the steeper channel gradient of the Mazák Stream. The values of other geometric parameters such as the step height and the wavelength were very close to those obtained for the Stoligy Stream (0.33 and 1.31 m in Mazák and 0.29 and 1.36 m in Stoligy, respectively). The parameter L/W ranges from 1.07 to 1.33 in the two streams, which shows that the bed pattern for both sites allows a transition between cascades and step-pools, sensu Montgomery and Buffington (1997). This implies that foliaged step-pools may be developed in other streams with similar geometric dimensions and conditions in deciduous Western Carpathian forests. Note, however, that Borák (2012) did not examine the occurrence of boulders or SW/LW in Mazák foliaged step-pools.

We observed a smaller step height (less than one half) than was described by Frandofer and Lehotský (2013) in the step-pool channels of the Slovakian Flysch Carpathians (0.4–0.6 m). The authors also documented a much longer distance between individual steps (4–6 m) at a mean channel gradient of 0.14 m/m. The bedrock step-pools investigated by Duckson and Duckson (2001) in very steep bedrock channels (0.25–0.35 m/m) composed of volcanic rocks (andesite, basalt and dacite) had similar step heights (0.2–0.33 m). In contrast, though, the step wavelength and $H/L/S$ ratio measured by these authors was much lower due to their steeper channel gradients. Abrahams and Atkinson (1995) originally reported that the $H/L/S$ ratio falls into the interval $\{1, 2\}$ for the adjustment to maximum flow resistance. This is consistent with our findings for foliaged step-pools with both boulders and SW. Significantly higher values with $H/L/S \geq 3$ were found in a large dataset of step-pool reaches in Idaho, USA (Chartrand and Whiting, 2000) and a value of 2.5 was obtained for the step-pool channel Cold Creek in California (USA) (Chin, 1999). In both cases, much higher step heights were observed (0.5–0.6 m). All other step-pool datasets had bankfull parameters and channel gradient values quite similar to the ratios at the Stoligy site, of $0.85 < (H/L/S) < 1.96$; these include three Californian step-pool streams (Chin, 1999), an Alpine torrent (Lenzi, 2001), step-pools from Arkansas (USA) (Nickolotsky and Pavlowsky, 2007), and step-pool reaches of French Alpine and Vogez headwater channels (Recking et al., 2012). Thus, foliaged step-pool systems are well adjusted to maximum flow resistance, similar to other steep headwaters. Step wavelength seems to be a dependent variable because the individual step heights are strictly influenced by lithological conditions; flysch lithology usually produces relatively finer sediments, creating smaller step heights (Galia and Hradecký, 2014).

5.2 Aspects of pool retention of the foliaged step-pool formations

The mean value of the relative foliaged depth in Stoligy was 33.4%. In comparison, Mazák had a relative foliaged depth of 27.3% (Borák, 2012). These results demonstrate that significantly higher volumes of water are stored in pools because of the presence of leaves in steps. Thus, leaf litter in headwater channels increases water retention in mountain landscapes covered by deciduous forests.

Sediments in pools of step-pool sequences are usually composed of fine gravel and sand (Montgomery and Buffington, 1997). We compared fine pool sediments from both foliaged and unfoliaged step-pool sequences because the presence of leaves in step-pool systems significantly affected pool depth. For Stoligy, we obtained three samples of sediments from unfoliaged pools and four from foliaged pools. We also analysed samples from Mazák, where 13 step-pool sequences were considered to be foliaged and eight were unfoliaged (Borák, 2012). A triangular graph displaying the ratio between gravel, sand and mud grain-size fractions shows obvious clusters of samples (Fig. 8). Samples coming from unfoliaged pools had a higher ratio of the coarsest fraction (in our case, gravel). The opposite situation is true of foliaged pools, which had a higher ratio of sand and mud. The finest fractions are transported past unfoliaged steps during ordinary discharges, whereas leaves in foliaged steps help to trap these fine fractions under the same discharge conditions. This implies that larger volumes of fine sediments are stored in foliaged pools than in unfoliaged ones. Differences in the absolute value of grain sizes between Stoligy and Mazák are most likely related to the different lithology of their sediment supplies, which creates a higher ratio of claystones in the Stoligy Stream; in addition, the two streams have slightly different hydrological conditions and bed material was sampled at different times.

5.3 Origin and stability of foliaged step-pool formations

It is important to investigate whether leaves are the principal factor that leads to well-developed step-pool morphology. We assume that foliage of bedforms leads to the formation of step-pool sequences rather than cascade or rapid channel-reach morphology. Foliaged step-pools are a kind of forced channel-reach morphology *sensu* Montgomery and Buffington (1997). We note that these step-pools have spatial and temporal dynamics. The role of leaves should be considered in the context of their volume in channels because variation in the amount of available leaves would thus determine the characteristics of step-pool morphology, including morphological aspects and stability. Based on the results of Hoover et al. (2006), we suggest that parameters such as the channel gradient, channel width, discharge and size of obstacles in the channels (boulders or SW/LW) are the main factors that influence the foliaged depth or step foliation. The biomorphologic effect of leaves would gradually decrease as discharge and channel width increase and as grain size parameters and channel gradient decrease.

We derived a qualitative model of the evolution and stability of leaf accumulations (Fig. 9), although we note that accurate values of critical conditions (i.e. discharge and flow velocity) for the transport of leaves and fine sediments remain unknown. The model assumes that transport is size-selective; for example, the grain diameter that will move depends on the critical discharge, which was observed in headwater streams in the Flysch Carpathians

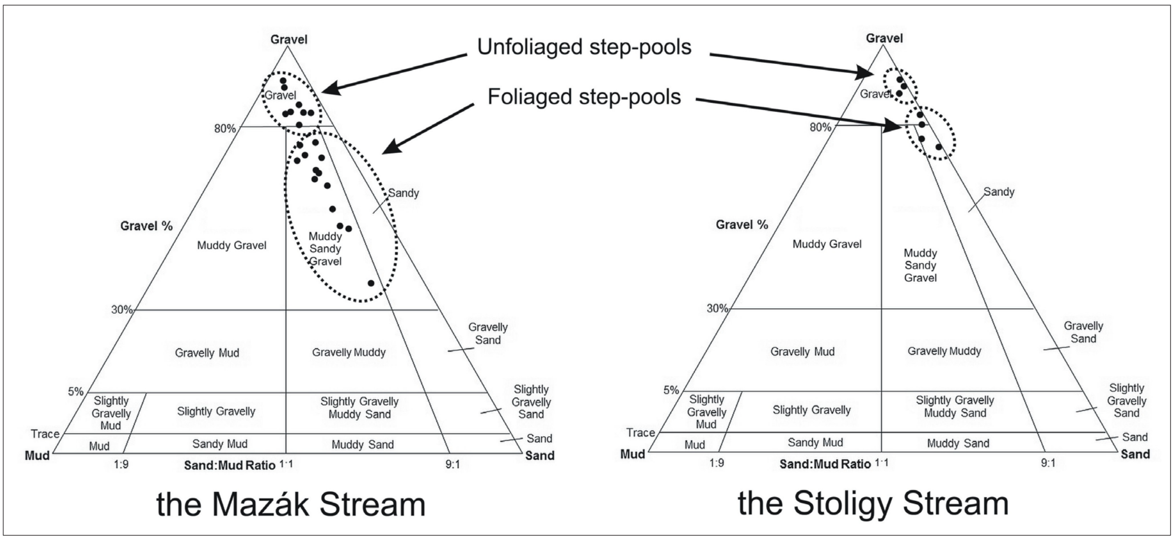

Fig. 8: Grain size characteristics of pools in both foliaged and unfoliaged step-pool formations. Foliaged formations contain finer material than unfoliaged formations. Source: authors' calculations

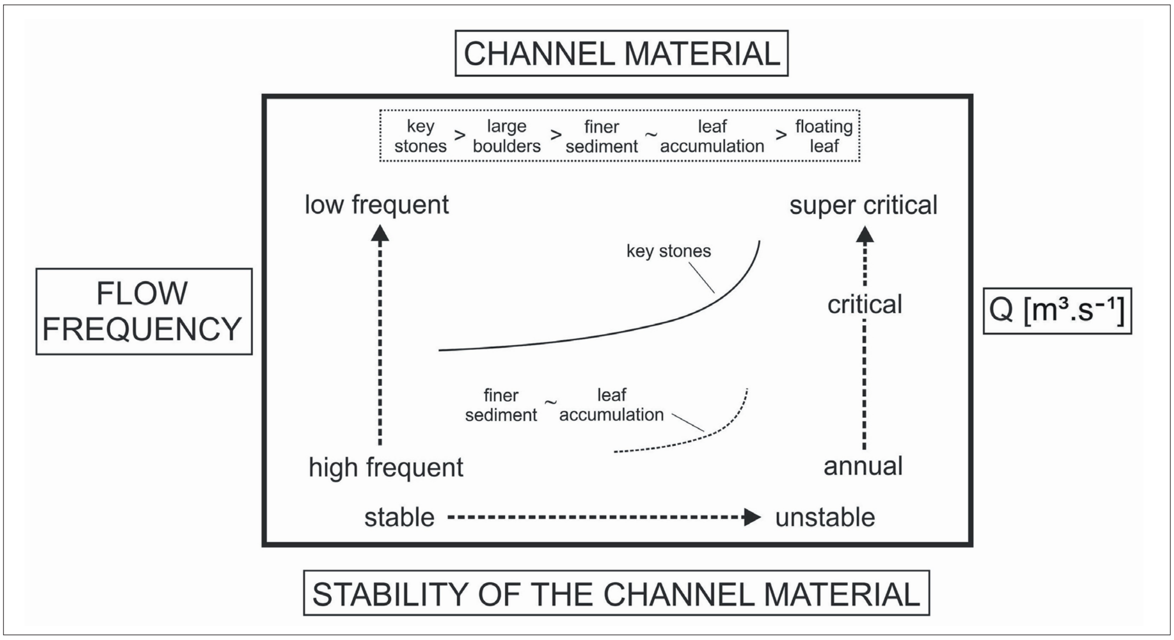

Fig. 9: Qualitative model of channel material transport in streams affected by leaves
Source: authors' conceptualisation

(Galia et al., 2015). The size-selective character of bedload transport is typical of well-developed step-pool channels (Montgomery and Buffington, 1997; Chin, 2003). There is evidence that leaves on boulder steps are covered by very fine sediments or that there is a mixture of leaves and fine sediments. This implies that: i) leaves were stored first, followed by storage of fine sediments; or ii) both types of material were accumulated simultaneously. The stability of individual patterns can be expressed in the following form: stable » key stones > large steps boulders (or LW/SW) > finer pools sediment ~ accumulated leaves > floating leaves » unstable. The model is dependent on the channel width, bed sediment calibre, heterogeneity or occurrence of instream wood, discharge regime and the presence of deciduous trees. Church and Zimmermann (2007) noted that the ratio between the channel width and sediment calibre in steep channels was crucial for development of regular step-pool morphology. For example, Galia and Hradecký (2014) found the ratio $W \leq 20.7\, d_{90}$ for step-pool reaches with flysch headwaters and relatively fine bed sediments. Thus, local steep streams in deciduous forests may develop contemporary step-pool reaches on higher W/d_{90} ratios because leaves fill the pores between individual bed grains during the autumn months. These forced step-pools occur until the leaves decay or are washed away during higher discharges (e.g. from snowmelt).

The origin of foliaged step-pool sequences can be described in three basic phases that depend on changes in flow discharge.

1. The first phase occurs during relatively low discharges in originally rapid, step-pool or cascade channels. Leaves are transported through the channel and randomly stored on steps, larger boulders, boulder clusters or pieces of SW/LW. Foliation and plugging of spaces between individual boulders occurs during this phase. The leaves are compressed by the flowing water and begin to create an isolated layer on steps, causing an

increase in water depth. The increase in step height lowers the flow velocity, leading to the development of pools above the steps. Water begins to flow over the crest of the steps and spaces between individual boulders are fully filled by compressed leaves. The leaves are not orientated randomly; they are mostly stored with the vertical direction of their main axis presented by a scape (Přibyla and Hradecký, 2009; Borák, 2012).

2. Leaves become more compressed during higher discharges in the second phase, when stabilisation of leaf accumulations on steps occurs. Massive isolation layers develop on the steps, connecting individual leaves to each other because of adhesive forces. Once a step is completely foliaged, water scour is concentrated into a narrow space on the step and has a high flow velocity. Fine sediments are stored in the pools and partially in the foliaged layer on the step.
3. The third phase commences when discharge increases; leaves begin to flow out of the steps as the threshold value of leaf stability is exceeded. Destruction of the leaf layer is accompanied by the release of fine sediments from the pools that were formed by the presence of leaves on steps. Removal of the leaves may destroy several step-pool sequences and the channel-reach morphology shifts to a rapid (or cascade) channel. The rest of the step-pool sequence involves a change in the water depth of the pools and a slight coarsening of the bed material in the pools. Leaves can begin accumulating again once discharge decreases and sufficient leaves are available in the channel.

Phases 1–3 are probably repeated many times during the year (Kochi et al., 2009), depending on conditions such as the discharge regime and delivery of leaves into the channels.

6. Conclusions

A new geomorphologic phenomenon was observed in forested steep mountain channels, in which leaf litter significantly affects the development of stepped-bed morphology and sediment transport processes. Step-pool sequences were the most common channel forms in the study area; these involved storage and compression of floating leaves into steps. The step-pool sequences were divided into groups of unfoliaged step-pools, boulder foliaged step-pools and small wood foliaged step-pools. Statistical analysis showed differences between foliaged and non-foliaged step-pool formations. Small wood step-pools accumulated more leaf litter than boulder step-pools. The accumulated leaves formed layers that increased the pool depth and affected the channel's hydrodynamics and transport of fine bed material. Particle-size analyses demonstrated that foliaged step-pool formations had finer sediment in the pools, which indicates that there are differences in sediment transport processes between foliaged and non-foliaged formations. Channel reaches often shifted from step-pool to rapid morphology after removal of leaves from their foliaged steps. This suggested that leaves were the main factor that caused the formation of well-developed step-pool sequences.

It is obvious that leaf litter plays an important role in headwater channels in deciduous forests but this is not well recognised. We conclude that the presence of leaves in the channel of forested watersheds affects water storage by increasing pool retention. Foliaged formations also create critical habitats for various biota, especially aquatic invertebrates that rely upon detritus inputs such as leaves as their main food sources. The presence of leaves in streams and its influence on channel units has great potential for further investigation and implications in forest management.

Acknowledgments

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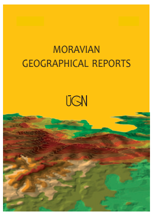

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DE GRUYTER OPEN

The effects of river patterns on riparian vegetation: A comparison of anabranching and single-thread incised channels

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Veronika KAPUSTOVÁ [a], Vladimír ŠALA [b]

Abstract

Riparian vegetation reflects the current conditions and the dynamics of streams. The floodplain vegetation along the watercourse of the Morávka River was subject to study in this project. In some reaches, the river has the natural character of an anabranching gravel-bed stream; in contrast, other Morávka R. reaches are incised into the bedrock. These cases were used to assess potential changes in vegetation conditions as evidence of negative processes taking place in the gravel-bed streams of the Beskydy Mts. The results demonstrate a higher biodiversity in the floodplain along the anabranching river channel. In contrast, the floodplain along the incised river channel shows low biodiversity values. Redundancy analysis was used to determine the relationships between plant species composition, distance from the main channel and relative elevation from the mean water level of the main channel. In addition, the results show a higher degree of change in plant species composition on the floodplain along the incised river channel. The analysis of floodplain groundwater fluctuations shows a decreasing trend in the annual maximum groundwater level.

Key words: *riparian vegetation, channel pattern, phytosociological survey, multivariate data analysis, the Morávka River, Outer Western Carpathians, Czech Republic*

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1. Introduction

Natural river landscapes represent one of the richest ecosystems in temperate zones (Forman and Godron, 1986). They are characterised by a unique combination of aquatic and terrestrial components, a mosaic of habitats and high biodiversity (Xiao et al., 2003). Erosion naturally occurs in all parts of the drainage pattern but, generally, river systems could be characterised by erosion in the uplands, downstream sediment transport and storage in the lowlands (Kondolf, 1997; Knighton, 1998). Complex environmental conditions, induced by geology, climate, hydrology and the morphology of channels and floodplain, affect the growth of vegetation in the fluvial landscape ecosystems (Králová, 2001). Vegetation classification based on the environmental conditions is one of the integral parts of landscape management and landscape research. A majority of these classifications is based especially on the water régime. Other factors are temperature (based on altitude) and trophic condition: see, for example, Plíva and Průša (1969) and Hančinský (1977) in the Czech Republic, Schönhar (1993) in Germany, or Hills (1966) in Canada.

These key factors also destroy, modify and build habitats and the associated riparian vegetation of river systems and influence disturbances important for the development of the floodplain environment (Naiman et al., 2005; Steiger et al., 2005; Tabacchi et al., 1998). Thus, vegetation is a good indicator of the present state of the environment, integrating diverse environmental influences and events that occurred in the past (Prach, 1994). An additional important factor is the effect of ground water, which affects the vegetation by its height levels, régime and quality (e.g. acidity, alkalinity or content of minerals.). This is one of the essential factors for the evaluation of changes in vegetation communities (Šeffer and Stanová, 1999).

Corridors of riparian vegetation along watercourses play an irreplaceable role in the landscape. They prevent flooding and bank erosion, and supply nutrients to habitats

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(Forman and Godron, 1986). In the case of changes in environmental conditions (e.g. alterations of water régime in the landscape, such as discharge régime changes or change of groundwater level connected with river channel incision or the elimination of flood flows), one can expect a change in the riparian vegetation, termed ecological succession. Ecological succession is an observed process of change in the species structure of an ecological community over time. The community begins with relatively few pioneer plants and develops through increasing complexity until it becomes stable or self-perpetuating as a climax community (Glenn and Lewin et al., 1992; Walker and Del Moral, 2003).

This article presents the results of our study of the riparian vegetation in the Morávka River floodplain area. The Morávka R. has experienced a rapid change in the last 50 years, when its active channel narrowed and massive incision took place. At present, the study area is characterised by two distinctive reaches of different development away from the originally anabranching gravel-carrying stream. The lower reach (0–7.0 r. km, see Fig. 1) is strongly affected by incision, but the upper reach (7.0–10.5 r. km, see Fig. 1) has partly preserved the original anabranching river pattern with lateral channel-migration. The main reasons for the massive incision of the lower reach (0–7.0 r. km) are strong anthropogenic impacts, namely river-channel control, bank stabilisation, and weir and valley dam construction (Galia et al., 2016; Škarpich et al., 2013; 2016). At 0–7.0 r. km, the anabranching channel pattern of the Morávka R. started to transform into a single-thread channel in the 1960s (the anabranching channel pattern is still visible in the aerial photograph from 1966, see Škarpich et al., 2013). The channel development has been influenced especially by the so-called Frýdek weir (at 1.25 r. km) and by the Konečný weir (at 2.31 r.km). Firstly, these weirs affected hydraulic conditions and the 'hungry water effect' (the term *sensu* Kondolf, 1997), which turned into incision downstream of these structures, as shown by observations and measurements (see Škarpich et al., 2013). Later, both weirs were destroyed by floods (the first one in 1949, the latter in the mid-1970s), and the river channel was gradually incised by upstream knickpoint retreat (for more detailed information see Škarpich et al., 2016). One important influence in the contemporary occurrence of the preserved original anabranching river pattern (7.0–10.5 r. km) is to a certain extent the Těšín-Hradiště Formation. This structural formation is represented by sandstone layers in the channel bedrock. These sandstone layers are more resistant to knickpoint propagation from the deeply incised reach. For more detailed analyses of channel changes in the Morávka River basin – see Škarpich et al. (2013) and Galia et al. (2016).

This paper provides an analysis of vegetation communities along two clearly contrasted river reaches (single-thread and anabranching channel patterns) based on a simple biodiversity assessment. The entire analysis was conducted on two transects (one in each of the contrasting river pattern settings), each with five data-points (compare to Solon et al., 2007). The main hypothesis is that channel incision processes are followed by a shift in environmental conditions (connected with the water regime in the landscape), which is reflected in a subsequent riparian vegetation change. The intense and temporally varying disturbances in the Morávka R. basin are continuously adjusting to new constraints of the floodplain environment. River incision eliminated the floodplain function and the periodical river inundation ceased to exist. These changes had to influence the plant species composition in the floodplain area. The main aim of this paper, then, is to analyse and compare environmental conditions and the distribution of plant species in the floodplain area along the respective river-channel patterns.

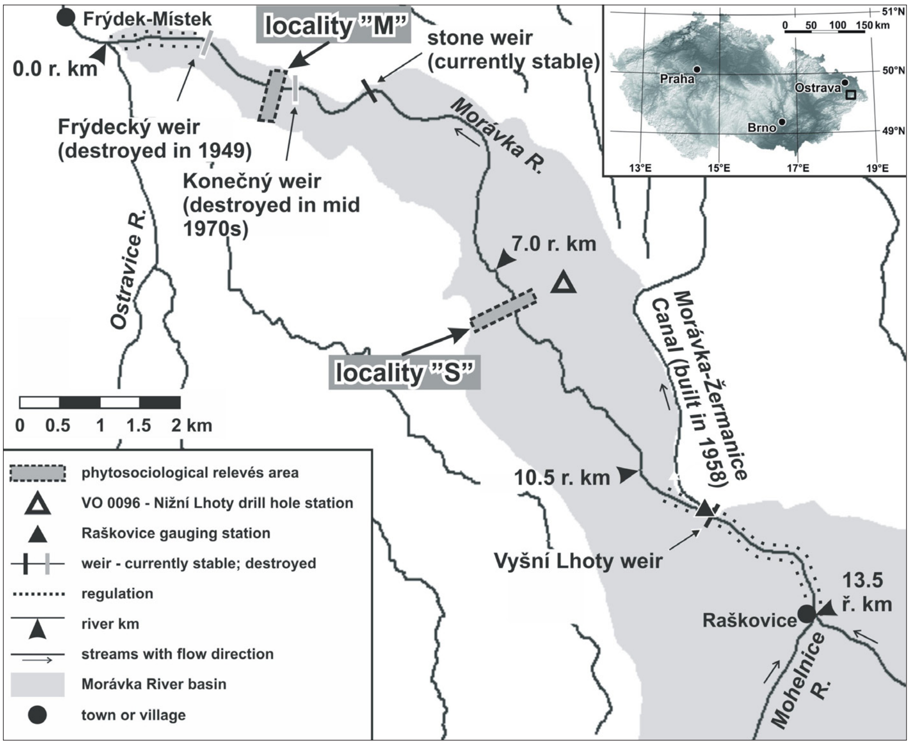

Fig. 1: Scheme of the lower Morávka R. basin with the location of analysed phytosociological relevés (transects) and water structures. Each transect shows approximate floodplain width in the analysed river reach
Source of data: T. G. Masaryk Water Research Institute; State Administration of Land Surveying and Cadastre; source: author´s elaboration

2. Regional settings

The Morávka River (see Fig. 1) is a gravel-bed stream 29.6 km in length that flows from the steep slopes of the Moravskoslezské Beskydy Mts. (MSB) to the flat piedmont. The annual precipitation in the basin ranges from 1,000 to 1,800 mm (data source: Czech Hydrometeorological Institute). The drainage area of the Morávka R. is 149 km^2. The mean annual discharge of the river reaches 3.73 m^3.s^{-1} at the Raškovice gauging station (upstream from the study area; for the location see Fig. 1), where the basin area is 131 km^2 (data source: Povodí Odry). The Morávka R. is characterised by the occurrence of frequent floods of moderate magnitude due to snow melting, and by the occurrence of rare heavy floods caused by cyclone-related summer rains. The study area is situated in the Podbeskydská Pahorkatina Hilly land built by the flysch Subsilesian and Silesian units of the Outer Group of Nappes (in the study area by the Upper Jurassic to Upper Cretaceous rocks) covered by Quaternary sediments (Menčík et al., 1983; Menčík and Tyráček, 1985; Picha et al., 2006). The flysch rocks of the Upper Jurassic to Cretaceous period belong in the Lower Těšín Member (prevailing silty-sandy and sandy claystones) and in the Tešín-Hradiště Formation (prevailing sandstones). The Upper Cretaceous rocks include the Frýdek Formation composed of calcareous shales and grey siltstones (Menčík et al., 1983; Picha et al., 2006).

The study area is part of the Western Carpathian subprovince – Podbeskydský bioregion (Culek, 2013). The dominant potential unit is represented by oak-hornbeam forests (*Tilio cordatae-Carpinetum*, Neuhäuslová et al., 1998; 2001). In the flat area around the town of Frýdek-Místek, oak-beech forests occur (*Carici-Quercetum*, Neuhäuslová et al., 1998; 2001). Chokecherry-alder forests dominate (*Pruno-Fraxinetum*) in the floodplain areas and the gravel alluvium is covered by willow forests (*Salicion eleagni*) (Culek, 1996). The herb layer is relatively rich in species, given by numerous oreophytes from the Moravskoslezské Beskydy Mts. These are represented by *Dentaria glandulosa* Waldst. et Kit, *Myricaria germanica* (L.) Desv., *Luzula luzulina* (Vill.) Racib., *Salix eleagnos* Scop. or *Hacquetia epipactis* (Scop.) DC (Culek, 1996).

3. Methods

The research is based on a phytosociological survey. In simple terms, the phytosociological survey is a group of ecological evaluation methods providing a comprehensive overview of both the composition and distribution of plant species in a given plant community (Concenço et al., 2013). The phytosociological survey is based on the collection of data from phytosociological relevés. We evaluated the riparian vegetation in the lower part of the Morávka R. basin using phytosociological relevés sized 10 × 10 meters after Randuška et al. (1986). We collected the data during April and May 2014. Experimental plots were located through transversal profiles close to the river channel (see Fig. 1) in: (i) the single-thread bedrock-incised channel (5 relevés, Fig. 2A and Fig. 3A; locality "M"); and (ii) the

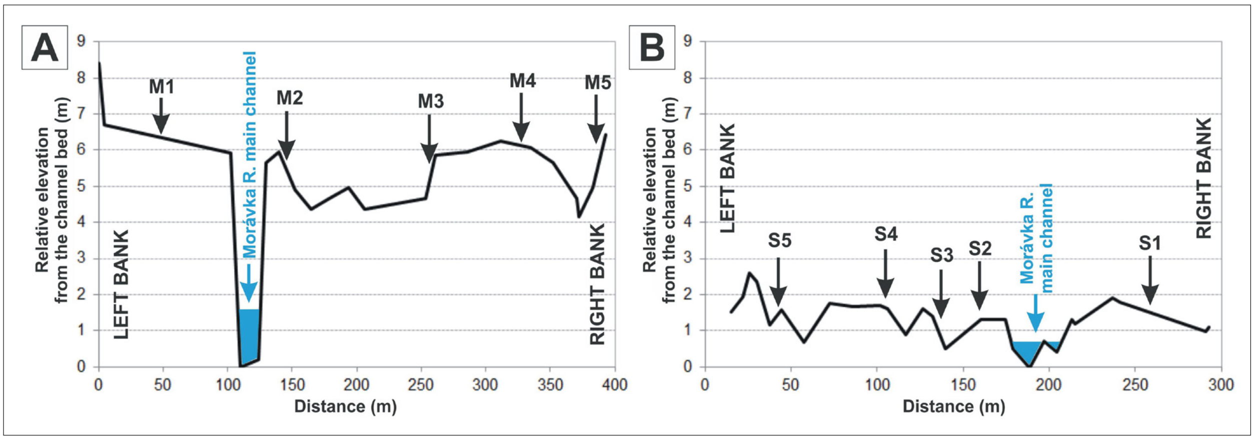

Fig. 2: Location of phytosociological relevés (M1–M5, S1–S5) in the cross section of the Morávka R. floodplain area: A – single-thread bedrock-incised channel; B – anabranching channel. Source: authors 'elaboration

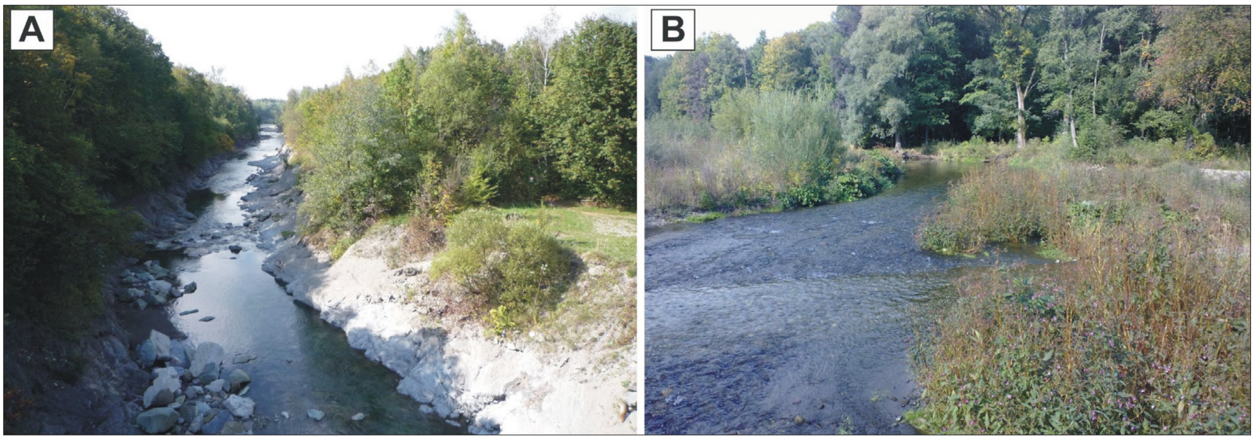

Fig. 3: The Morávka R.: A – single-thread bedrock-incised channel river; B – anabranching channel river reach Photo: V. Škarpich

anabranching channel (5 relevés, Fig. 2B and Fig. 3B; locality "S"). For the analysis, we collected data on the species composition in the herb layer.

We applied the Shannon-Wiener (Shannon and Weaver, 1949) and Simpson's (Simpson, 1949) indices of biodiversity for the analysis of species distribution. Both indices are quantitative measurements reflecting how many different species occur in a dataset, and simultaneously take into account how often the basic entities (such as individuals) are distributed among those types. The Shannon-Wiener index emphasises the richness component of diversity, while Simpson's index places emphasis on the evenness component (Shannon and Weaver, 1949, Simpson, 1949). Generally, the selection of the Shannon-Wiener index or Simpson's index can be problematic and both indices are commonly used for assessing biodiversity (Nagendra, 2002). Both indices can be very similar or, in very specific cases, they can show a considerable variation in response to changes in landscape richness and evenness (Nagendra, 2002). In this study, we used both indices to obtain stronger results.

Following Randuška et al. (1986), we transformed the data for each plant species from the ordinal phytosociological scale acquired to a quantitative phytosociological scale calculating the mean percentage coverages in each relevé. Firstly, the Shannon-Wiener Index was used to quantify the entropy, defined as:

$$H = -\ sum(p_i \ ln \ p_i),$$

where p_i is the proportional abundance of species i (Shannon and Weaver, 1949). Secondly, the Simpson's Index (Simpson, 1949) was used to measure the degree of concentration when individuals are classified into types and it is defined as:

$$\lambda = sum \ p_i^2.$$

For the statistical analysis we used the R software environment (R CORE TEAM, 2012) and the function package Vegan (Oksanen et al., 2013). For the Shannon-Wiener index calculation we applied the *diversity ()* function with the following settings:

diversity (releve_N, index = "shannon", MARGIN = 1, base = exp(1)),

and for the Simpson's index calculation we applied the diversity () function with the following settings:

diversity (releve_N, index = "simpson", MARGIN = 1, base = exp(1)),

where *releve_N* is a given phytosociological relevé.

We evaluated the channel effects on the riparian vegetation conditions using multivariate data analysis. For this purpose, the phytosociological data were transformed into a logarithmic scale. The phytosociological data (as explanatory variables) include the percentage coverage of given plant species in the given phytosociological relevé. For the transformation, we used the logarithmic equation after Anderson et al. (2006) in order to increase the importance of rare species:

$$x' = log_2 (x)+1,$$

where x is the mean percentage coverage of a given plant species in a given relevé. In the context of the importance of vegetation response to channel-floodplain conditions, the following environmental variables were selected as response variables for the analysis: phytosociological relevé distance from the main channel with flowing water, and relative elevation of a phytosociological relevé from the water level in the main channel, where the main channel of anabranching pattern was considered to be the one containing the highest volume of water during the mean annual discharge. As a first step, detrended correspondence analysis (DCA) was carried out in order to determine the gradient length and thus to select a proper ordination method for further analyses. Gradient length shows the length of the first ordination axis in the n-dimensional space. The first ordination axis is defined in the space such that it reflects the maximum variability of the dataset (on this axis, a maximum variance is detected). Hill's scaling (Hill and Gauch, 1980) is performed within DCA, so the length of different ordination axes is comparable for different datasets. The gradient length values show the potential to use specific ordination methods, which are based either on a model of linear species response to the underlying environmental gradient (redundancy analysis, RDA), or on a model of unimodal species response (canonical correspondence analysis, CCA) (Lepš and Šmilauer, 2000). We used the *decorana ()* function from the package Vegan for DCA (Oksanen et al., 2013):

decorana (releves),

where *releves* is a dataset containing the logarithmically transformed percentage coverage of a given plant species in a given relevé. A gradient length value of 2.03 was discovered for areas along the anabranching river channel, and 1.60 for floodplain areas along the single-thread bedrock-incised channel. Over a short gradient (< 3.00), a linear approximation works well, but over a long gradient (> 4.00) the approximation by the linear function is poor (Lepš and Šmilauer, 2000). A gradient length from 3.00 to 4.00 is defined as a transitional boundary between the linear and unimodal methods. From this point of view, the use of the linear method (RDA) was appropriate.

The RDA provides a model of linear species response to the underlying environmental gradient. The RDA enables the investigator to quantify the effect of known variables (in this case, the explanatory variables are distance from the main channel and relative elevation from the water level) on response variables (species composition of phytosociological relevés). We used the *rda ()* function from the package Vegan for the RDA (Oksanen et al., 2013):

rda (releves~distance),

rda (releves~elevation).

The analysis of groundwater level changes helped us to detect the floodplain hydrological conditions since 1963. Only one drill well gauging station (VO 0096 – Nižní Lhoty) was available in the Morávka R. floodplain (for the location – see Fig. 1). Data for groundwater levels from 1963 to 2008 were provided by the Czech Hydrometeorological Institute.

4. Results

The Shannon-Wiener and Simpson's indices show higher values of species diversity in the floodplain area along the naturally anabranching river channel than in the floodplain area along the single-thread bedrock-incised channel (see Tab. 1, Fig. 4). In floodplains along the anabranching channel, the mean value of the Shannon-Wiener index is 2.465 and the mean value of the Simpson's index is 0.901. By contrast, in floodplains along the single-thread bedrock-incised channel, the mean value of the

Shannon-Wiener index is 2.309 and the Simpson's index mean value is 0.887. Median values of Shannon-Wiener and Simpson's indices are similar (Tab. 2). The two indices exhibit a very strong correlation ($r^2 = 0.97$). Though the Simpson's index is more weighted on dominant species as compared with the Shannon-Wiener index (Shannon and Weaver, 1949; Simpson, 1949), both indices demonstrate a very similar situation.

The subsequent RDA shows that the environmental variable "Distance from the main channel with flowing water" has a higher power to explain the plant species composition. In the floodplain area along the single-thread bedrock-incised channel, the plant species composition is explained by 44.46% ($p = 0.008$), and in the floodplain area along the naturally anabranching river channel pattern, the plant species composition is explained by 32.26% ($p = 0.317$). These results indicate that incision processes result in a more rapid change in the plant community composition with increasing distance from the main channel.

Similar results (but not statistically significant) were obtained for the RDA of "Relative elevation from the water level in the main channel". Relative elevation explains the

River-channel pattern	Phytosociological relevé	Shannon-Wiener Index	Simpson's Index	Distance from the main flow of the Morávka River (m)
Single-thread bedrock-incised channel	M1	2.187	0.873	62
	M2	2.552	0.915	31
	M3	2.378	0.896	152
	M4	2.286	0.888	217
	M5	2.140	0.861	264
Anabranching channel	S1	2.427	0.897	55
	S2	2.330	0.886	35
	S3	2.649	0.920	55
	S4	2.586	0.915	86
	S5	2.332	0.890	141

Tab. 1: The Shannon-Wiener and Simpson's indices of phytosociological relevés in the study area of the Morávka River floodplain. Source: authors' calculations

Phytosociological relevés	Arithmetic mean		Median	
	Shannon-Wiener Index	Simpson's Index	Shannon-Wiener Index	Simpson's Index
Floodplain area of the single-thread bedrock-incised channel (M1–M5)	2.309	0.887	2.286	0.888
Floodplain area of the anabranching channel (S1–S5)	2.465	0.901	2.427	0.897

Tab. 2: Central tendency measures of the Shannon-Wiener and Simpson's indices for the analysed transects in the study area of the Morávka River floodplain. Source: authors' calculations

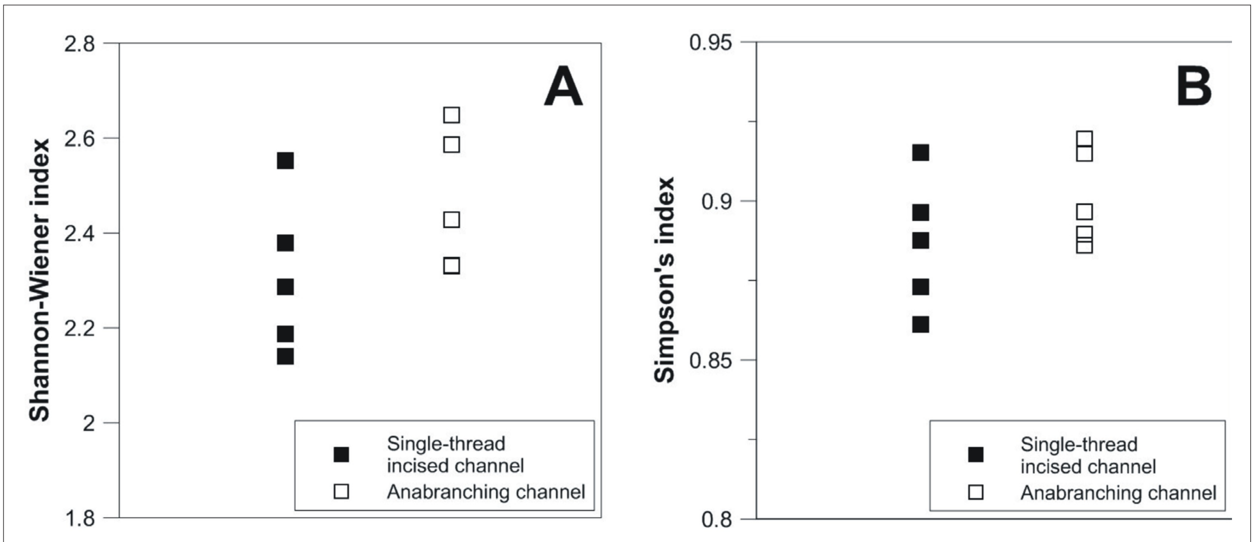

Fig. 4: A – Shannon-Wiener index and B – Simpson's index of phytosociological relevés in the study area of the Morávka River floodplain. Source: authors' elaboration

plant species composition by 19.73% ($p = 0.533$) in the floodplain area along the single-thread bedrock-incised channel, and by 14.93% ($p = 0.767$) in the floodplain area along the naturally anabranching river channel pattern.

In addition to the above-mentioned findings, the analysis of groundwater levels revealed significant results about the changing hydrological conditions in the Morávka R. floodplain. Figure 5 shows the variation of maximum annual groundwater levels at the VO 0096 – Nižní Lhoty drill well gauging station (for the location see Fig. 1). There is a visible decreasing trend of maximum annual groundwater levels (see Fig. 5A) during the years 1963–2008: the equation of the linear trend of maximum annual water levels is $Y = 369.94 - 0.0065X$ ($r^2 = 0.1958$, $p = 0.0019$).

5. Discussion

These results suggest that different plant habitat conditions occur in the incised channel reach and in the anabranching channel reach. Periodical inundation in the lower Morávka R. basin was stopped by river channel incision (Škarpich et al., 2013). Simply by comparing the Shannon-Wiener (Shannon and Weaver, 1949) and Simpson's (Simpson, 1949) indices, we can see there are differences in biodiversity between the two analysed floodplain areas. These results demonstrate a larger variety of habitat conditions in the floodplain area along the anabranching river channel. The habitat conditions are represented especially by terrestrial and semi-terrestrial habitats (sensu Hupp and Osterkamp, 1985; Hupp and Bornette, 2003), affected by periodical inundation with dry and wet periods (with terrestrial and semi-terrestrial conditions, respectively). Consequently, biodiversity is higher in the floodplain along the anabranching river channel (sensu Mikuś et al., 2013). On the other hand, the absence of floodplain periodical inundation (as along the bedrock-incised channel) leads to reduced biodiversity with plants fixed especially to terrestrial conditions.

Groundwater level is a crucial environmental factor influencing the plant species composition connected with the terrestrial and semi-terrestrial habitats (O'Brien and Currier, 1987). The logic behind using the “distance from the main channel with flowing water” and the “relative elevation from the mean water level in the main channel” as environmental variables in the RDA analysis is that the channel and the floodplain communicate together hydraulically. The water content in the floodplain decreases with increasing distance or elevation from the main channel. Comparing the floodplain areas along the two respective river patterns (anabranching channel and single-thread incised channel) we demonstrated that incision processes cause a more rapid change in the plant community composition with increasing distance from the main channel. This suggests that groundwater conditions could be affected by the river incision through the gradual relative sinking of water level in the river channel – relative to the floodplain level.

The analysis of maximum annual groundwater levels acquired from the drill well gauging station close to the anabranching river channel at the Morávka R. floodplain can be characterised by a decreasing trend (see Fig. 5A). It partially depends on the decreasing frequency and magnitude of flood discharges in the study area. The Morávka R. was characterised by high discharge variation (approximately 1:4,000 between minimal and maximal discharges; Source: Povodí Odry) before the completion of the Morávka-Žermanice Canal and the Morávka Valley Dam (Fig. 5B). The Morávka-Žermanice Canal (for the location see Fig. 1) diverts the water flow into the neighbouring Lučina River basin. After the completion of the canal in 1958, the maximum annual discharge visibly decreased (see Škarpich et al., 2013 and Fig. 5B), supported also by the functioning of a valley dam built in 1969. The interrupted trend in the maximum annual discharge in 1997 resulted from a disastrous flood in that year (the 20- to 50-year flood); the peak discharge of this flood was only slightly mitigated by the valley dam. The decreasing trend of groundwater level affects the content of water in the floodplain, which is gradually drying out.

6. Conclusions

We assessed the riparian vegetation and floodplain conditions in the Morávka R. study area: (i) by the statistical analysis of biodiversity indices; (ii) by RDA statistical testing

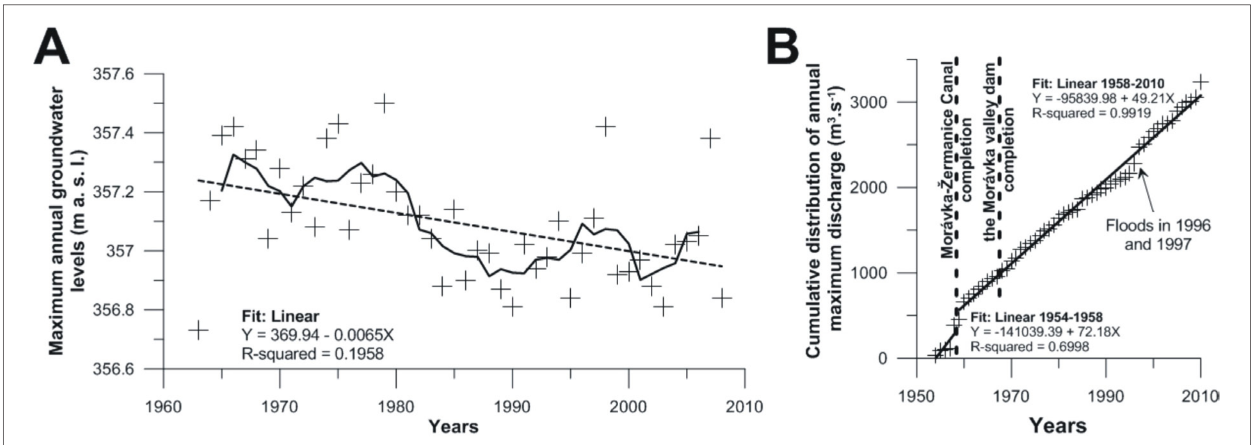

Fig. 5: A – Maximum annual groundwater levels in the years 1963–2008 at the VO 0096 – Nižní Lhoty drill well gauging station (for the location see Fig. 1)
Note: cross symbols (+) = maximum annual groundwater levels, solid line = five point running mean, dashed line = linear trend); B – Cumulative distribution of annual maximum discharge of the Morávka R. at the Raškovice gauging station (for the location see Fig. 1; cross symbols (+) = cumulative distribution of annual maximum discharge; modified from Škarpich et al., 2013)
Source: Data – Czech Hydrometeorological Institute; authors’ elaboration

of plant species composition and its dependence on distance from the main channel and relative elevation from the water level of the main channel; and (iii) by analysing the groundwater levels from the selected monitored drill well. We found that the diversity of plant species of the floodplain along the anabranching channel is higher than in the floodplain along the single-thread incised river channel. We demonstrated the dependence of plant species composition on distance from the main channel in the floodplain along the single-thread incised river channel. The plant species composition is more rapidly determined by distance from the main channel and relative elevation from the mean water level of the main channel in the floodplain area along the incised river channel. This finding refers to the changing conditions of groundwater levels affected by the incision of the river. Groundwater conditions are affected also by a generally decreasing trend of groundwater levels, and this contributes to a gradually drying out of the Morávka R. floodplain.

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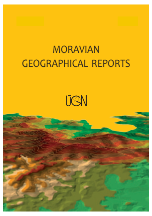

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DE GRUYTER OPEN

Channel migration inferred from aerial photographs, its timing and environmental consequences as responses to floods: A case study of the meandering Topľa River, Slovak Carpathians

Miloš RUSNÁK [a] *, Milan LEHOTSKÝ [a], Anna KIDOVÁ [a]

Abstract

The bank erosion area, rate of bank retreat and overall geomorphological and financial effects of channel migration due to recent flood events (over the time span 1987–2009) are identified using remotely sensed data and GIS. A 39 km-long reach of the meandering, gravel bed Topľa River (Flysch Slovak Carpathians) was selected as the study area. Based on the analysis of culmination discharges, two different flood periods are identified. The first one (1987–2002) is characterised by the dominance of low magnitude flood events, compared to the second one (2002–2009) with higher magnitude floods. Aerial photographs from 2002 and 2009 were chosen as a way to capture the morphological changes that occurred after the flood periods, while those from 1987 served as the reference point. In total, an area of 85.2 ha was eroded and 60.1 ha were deposited. The average channel shift per year doubled from 0.8 m/year (1987–2002) to 1.6 m/year (2002–2009). The most eroded land cover category in the riparian zone is floodplain forest, followed by arable land, grasslands and pastures and shrubs. From an economic point of view, the eroded floodplain with arable land and grassland (€ 29,924.02 in total) is a negative consequence of channel migration.

Key words: *river channel migration, flood, bank erosion, land cover, erosion risk, Slovakia*

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1. Introduction

Most river channels develop bends in reaches with erodible materials and low gradient. Flow energy in such sinuous channels is concentrated along the concave bank in bends, while deposition occurs at the convex one. Fast-moving water on the outside bend erodes the bank, picks up the sediment and drops it when the water slows at the inside of the next downstream bend. This increases the length of the channel, which helps dissipate the energy of the flowing water over a longer distance. Streambank retreat, frequently called streambank erosion, occurs by a combination of three processes: subaerial processes, fluvial entrainment and mass wasting. To provide clarity for the remainder of the article, the authors have adopted the terminology proposed by Lawler et al. (1997). Specifically, the terms "fluvial erosion" and "fluvial entrainment" are used to describe the detachment, entrainment and removal of individual soil particles or aggregates from the streambank face by the hydraulic forces occurring during flood events. The terms "bank failure" or "mass wasting" denote the physical collapse of all or part of the stream banks as a result of geotechnical instabilities. Bank erosion and bank failure commonly work in concert to produce bank retreat.

Thus, bank erosion on one hand and deposition/reworking of bank-attached geomorphic units along the convex bank on the other hand, promote lateral migration of the channel. Studies have shown that the sediment from stream banks counts for as much as 85% of watershed sediment yields and bank retreat rates as high as 1.5 m^{-1},100 m/year (Simon et al., 2000). In addition to water quality impairment, stream bank retreat impacts floodplain residents, riparian ecosystems, bridges and other stream-side structures. River bank erosion is seen as a part of long-term channel change, meander migration and floodplain development and destruction.

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In recent years, floods following heavy precipitation have occurred with increasing but unpredictable frequency in many European countries. Many authors (e.g. Bronstert, 2003; Brázdil et al., 2006; Langhammer, 2010; Pekárová et al., 2003, 2010) point out the cyclical character of flood events and have identified several dry and wet periods during the last century in many world and Slovak rivers. Dry and wet periods are likely to be conditioned by the North Atlantic Oscillation (NAO) phenomenon (Pekárová, et al., 2010).

Hence, understanding streambank erosion hazards in response to recent floods calls for analyses of the links between floods and river behaviours at the regional to local scale (Langhammer and Vilímek, 2008; Brázdil et al., 2011). The long-term response to a series of flood events manifests itself first in the inner-channel organisation of landforms. The temporal distribution of flood events reflects the overall climatic conditions of the region and responds to the precipitation regime. The impact of floods depends on the morphological state of the channel (sinuosity, pattern, gradient) during high flow events, and the geological and morphological (topographical) conditions of the river catchment (Hooke, 2015). Further variables which affect the response of the channel system to floods, are changes in vegetation cover (succession, seasonality and land use), as they partially influence the sediment supply or flood capacity of the channel. Similar floods in terms of magnitude and frequency, however, can produce dissimilar morphological responses (Fuller, 2008). Michalková et al. (2011) point out the significant geomorphological effect of a critical shear stress, which is recorded under the influence of more frequent and prolonged floods. Hickin and Sichingabula (1988) highlight the importance of the flood duration. In general, they consider that smaller but longer duration floods are more constructive, while high magnitude floods are destructive. The effects of small magnitude and frequent floods are constructive and contribute to accretion of sediments and stabilisation of the channel (Corenblit et al., 2007).

Bank erosion is closely connected with flood events characterised by the increase of stream power. It leads to an increased rate of erosion/deposition processes in the channel (Hooke, 1979; Miller, 1990; Hrádek, 2000; Richard et al., 2005; Larsen et al., 2006; Kiss et al., 2008; Pišút, 2008). Bank erosion processes depend on the size of the discharge and the interactions between the ever-changing hydrological conditions (the flow velocity, local hydraulics, floods and their magnitude, frequency, duration and timing) and other factors contributing to bank erodibility (initial bank geometry, planform geometry, height and density of vegetation, volume of accessible sediments, sediment grain size) (Knighton, 1998; Russell et al., 2004; Luppi et al., 2009), as well as floodplain land cover and overall riverine landscape management.

The successful and sustainable management of rivers requires awareness of which river reaches are prone to bank destruction and any subsequent lateral shifts (Brierley and Fryirs, 2005; Richard et al., 2005; Fryirs and Brierley, 2013). Piégay et al. (2005) report several ways of delimiting the erodible corridor. Historical analysis based on data obtained by remote sensing and historical maps, offers an ideal source for the definition of river channel mobility and the identification of both stable and unstable reaches. It is less applicable, however, for the prediction of future instability and lateral shift.

Aerial photos capture high-resolution details of the changing fluvial landscape (Bryant and Gilvear, 1999). The greatest advantage though, is their temporal and spatial flexibility in the mapping of changes. Their benefit lies in the accessibility of dense and highly accurate information (dependent on resolution), which allows relatively precise quantification of morphological processes (bank erosion, planform changes, bar accumulation, etc.). The accuracy and precision of spatial data, methods for calculating lateral movement of the channel and the selection of consistent rules for identifying landform dynamics and delimiting the features of interest, significantly affect geomorphological interpretations (Zanoni et al., 2008). Not only do historical data serve to identify lateral migration (Hooke, 1979; Pišút, 2002; Gilvear and Bryant, 2003; Michalková et al., 2011), but they also contribute to the study of changes of channel and riparian zone patterns (Bryant and Gilvear, 1999; Gilvear and Willby, 2006). Floods and their erosional power affect the overall ecological diversity in the riparian landscape by eroding channel landforms or vegetation in the riparian zone, by depositing sediments and seed dissemination (Ward et al., 2002; Gurnell and Petts, 2002, 2006; Corenblit et al., 2007; Opperman et al., 2010; Corenblit et al., 2010; Erskine et al., 2012).

The aim of this paper is to identify bank erosion areas, the rate of bank retreat and its financial consequences. The paper also investigates the links between bank erosion and land cover categories in the riparian zone, and the overall geomorphological effects of channel migration and its timing, due to recent flood events between 1987 and 2009 in a gravel bed, minimally regulated and laterally partly-confined meandering watercourse.

2. Study area

The research has been carried out over a 39 km central reach of the Topľa River, a gravel-bedded, non-regulated channel (Fig. 1) in the outer Carpathians flysch setting in Eastern Slovakia (Central Europe). The river springs at an altitude of 1,015 m a.s.l. in the mountain range of Čergov. It is 115 km long before it reaches the point of confluence with the River Ondava. The area of its basin is 1,506.4 km^2; the long-term daily average discharge at the Bardejov gauging point oscillates at a level of Q = 3.018 $m^3.s^{-1}$ (Qmax = 350 $m^3.s^{-1}$ (17. 05. 2010)). The Topľa River in the study reach is a 6^{th} order stream (Strahler order). The catchment is built by Eocene claystones, sandstones and conglomerates. The floodplain of the Topľa River is filled with Holocene gravels and sandy gravels and the valley slopes are affected by landslides. The thickness of the layers varies between 2–8 m (Kováčik et al., 2011).

The river basin is considerably forested with a total cover of 52% (CORINE land cover 2006). Agricultural landscape is represented by the category of arable land, concentrated along the valley bottoms, and covers 24.4% of the catchment. Dikes are built on the left bank near the town of Giraltovce (length 670 m) and in the town of Bardejov (length 150 m). A small hydropower plant was constructed between 1987 and 2002 in a meandering reach of the river south of Bardejov. Stony bank revetments were built in several places (to a total length of 1,990 m) where the river threatened roads, bridges or arable land. These bank protection practices were mapped: the longest bank revetment is 300 m long. These works only have a very local effect, however, and the Topľa preserves its natural state.

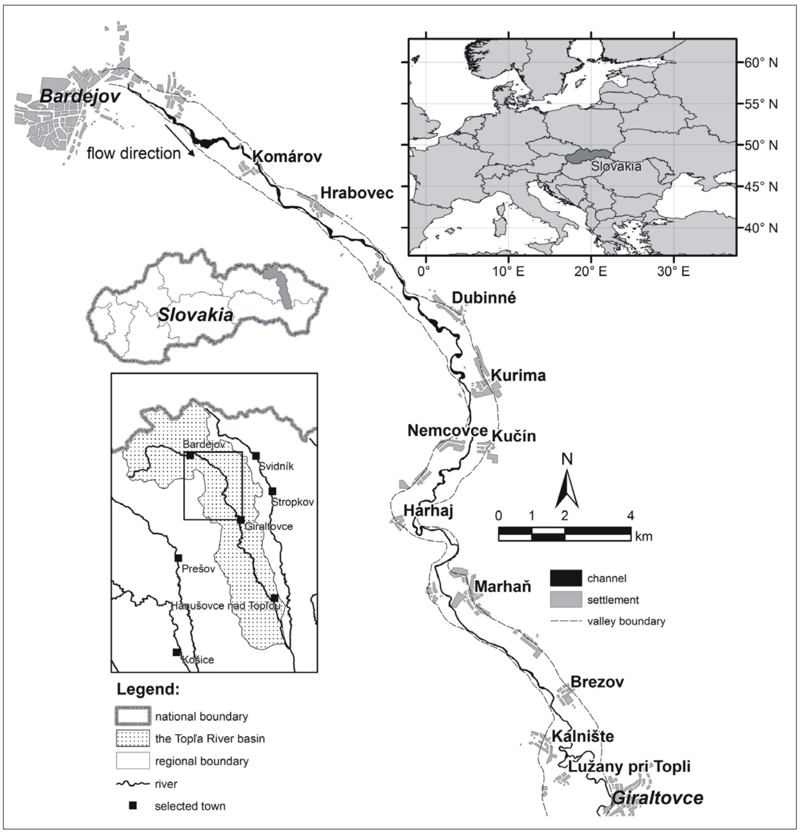

Fig. 1: Location of the Topľa River catchment and the study reach. Source: GIS data: Geodesy, Cartography and Cadastre Authority of Slovak Republic (122-24-99-2012); authors´ elaboration

3. Methods

The post-flood period serial geomorphic analysis (POPSEGA, Kidová et al., 2016) approach has been used as the methodological template. The analysis of daily average discharges (data provided by the Slovak Hydrometeorological Institute (SHMÚ) from the Bardejov gauging station located immediately upstream from the study reach) and the analysis of culmination discharges (which were defined as the 3rd level of flood alert declared by the SHMÚ), allowed us to identify two different flood periods. The first one (1987–2002) is characterised by the dominance of low magnitude events, whilst during the second one (2002–2009) higher magnitude floods are typical.

Spatial data about the channel, the in-channel landforms and the riparian zone land cover were generated from remote sensing images (aerial photographs and orthophotographs). The photographs were chosen in such a way that the morphological changes that occurred after flood periods were captured. They were analysed in three time horizons (1987 as reference,and 2002 and 2009 as the post-extreme flood events) applying ArcGIS in the S-JTSK (Krovak East North) coordinate system. Black-and-white aerial photographs (taken on July 7, 1987 and August 23, 1987, pixel resolution 0.5 m) and colour orthophotos (second half of June 2002 with pixel resolution 1 m, and from April 15, 2009, pixel resolution of 0.89 m), were the sources of spatial data. Aerial photographs were taken at similar low flow conditions, which is important to minimize differences caused by varying water levels during vectorisation of channel landforms (mainly gravel bars, Tab. 1). Discharges at the time of imagery were similar to the average daily discharges. A limitation of the method is that the images capture the state of the channel at the moment of imaging and do not record the process of changes that take place between individual events; this leads to a problem with the assessment and definition of changes and the identification of the contribution of individual change attractors (Hooke and Redmond, 1989; Draut et al., 2011).

The raster sources obtained were used to identify the bank edge (channel); the in-channel forms (bars) and the land cover structures of the riparian zone. The bank edge was traced either along the visible bank line or, in the case of the canopy cover impeding its distinct position, it

	Daily average Qa (1967–2009) Hd (1987–2009)	**Date of aerial photograph**					
		1987		2002 (15.–30. 6.)		2009	
		7/7/1987	23/8/1987	max.	average	15/4/2009	26/8/2009
discharge Qa [$m^3.s^{-1}$]	3.017	1.975	1.439	2.259	1.465	4.078	1.485
water level Hd [cm]	155.1	155.3	151.54	156	150.76	159	149

Tab. 1: Hydrological characteristics of the River Topľa at the Bardejov gauge station (daily average discharge (Qa) and daily average water level (Hd) on the date of aerial photographs. Spatial data were recorded during similar flow conditions. Source: Data (Slovak Hydrometeorological Institute)

was drawn in an approximate position based on the field survey of the treetop size. Bank erosion was assessed by overlapping bank positions in three time horizons according to the methodology of Lehotský et al. (2013) and Rusnák and Lehotský (2014). The spatial aspect of the individual parameters of the lateral shift, gravel bars and bank erosion was expressed for 250 m segments (154 up-stream numbered segments in total). During the field research trips (2011–2014), individual morphological forms and processes were identified. Thus, data were gained about the erosion and the deposition area, as well as the direction and the size of the individual bank shifts. As for in-channel landforms, four types of channel landforms were identified: a) lateral bars, b) point bars, c) central bars, and d) islands. The main criterion for distinguishing between bars and islands was vegetation cover. Bars were identified as landforms without vegetation or low vegetation cover of less than 25%, and islands with a tree vegetation cover of more than 70%. The resolution of raster data influenced the amount of detail and the size of interpretation objects. The limit for identification of lateral shift was 1 m (1 pixel) and the landforms were digitised if one dimension exceeded 3 m (3 pixels).

The land cover of the riparian zone was investigated in the buffer zone of 20 m away from the bank lines obtained for 1987, 2002 and 2009. Its width, 20 m, is considered the floodplain space sufficient to capture bank line shift during the study time span. In total, five land cover categories were defined:

1. riparian forest (tree cover more than 70%) as a mature stage of the development in the riparian vegetation;
2. shrubs;
3. grassland and pastures;
4. arable land; and
5. urbanised areas (built-up surfaces, among which gardens, urban greenery or other man-made technical structures can be found).

The social aspect of bank erosion was assessed according to the monetary value of destroyed plots, which is defined by the Decree of the Ministry of Agriculture and Rural Development of the Slovak Republic about prices of plots and growths on such plots for the purpose of land consolidation (Decree No. 38/2005). This Decree contains prices set by the Government. The prices are based on the soil quality of plots classified by the so-called bonity soil-ecological units. The values of plots were established only for categories 3 and 4 (grassland and arable land). Forests in the buffer zone (categories 1 and 2) were excluded because they are not economically exploited. The economic value established by this method reflects the prices set by the Government, which differ from market prices.

4. Results

4.1 Analysis of flood events

Mean daily discharges oscillate around 3.018 $m^3.s^{-1}$, but the maximum discharge in the relevant period of 1987–2009 was 235 $m^3.s^{-1}$ in May 1987 (20-year recurrence interval, RI20). After the distinct flood event of 1987 and the flooding in 1989 (with a 5-year recurrence interval, RI5), there was a period of reduced flood activity with the maximum discharge corresponding to a 1 or 2-year recurrence interval (Fig. 2). Flood events of greater importance appeared after the year 2000 and particularly in 2004 (Q_{dmax} = 207 $m^3.s^{-1}$ [20-year recurrence interval]), 2006 (Q_{dmax} = 160 $m^3.s^{-1}$ [10-year recurrence interval]) and 2008 (Q_{dmax} = 218 $m^3.s^{-1}$ [20-year recurrence interval]). Larger floods also appeared in 2000 (Q_{dmax} = 92 $m^3.s^{-1}$ [from 2 to 5-year recurrence interval]), 2001 (Q_{dmax} = 76 $m^3.s^{-1}$ [2-year recurrence interval]), 2002 (Q_{dmax} = 82,1 $m^3.s^{-1}$ [from 2 to 5-year recurrence interval]) and in 2005 (Q_{dmax} = 103 $m^3.s^{-1}$ [from 2 to 5-year recurrence interval]). Based on the above, two different flood periods, i. e. 1987–2002 and 2002–2009 were identified. The first flood period (1987–2002) is characterised by the occurrence of the floods from a 1 to 2-year recurrence interval. The second flood period (2002–2009) represents a series of high magnitude and high frequency flood events with a recurrence interval from 5 to 20 years. The periods correspond to wet and dry periods identified by Pekárová et al. (2010).

4.2 Bank lateral shift and changes in bedforms

A typical feature of the Topľa River channel is its lateral dynamics and distinct bank erosion. In total, an area of 85.2 ha was eroded and 60.1 ha was deposited (the area of the former channel which became a part of the floodplain) in the period 1987–2009 (Tab. 2).

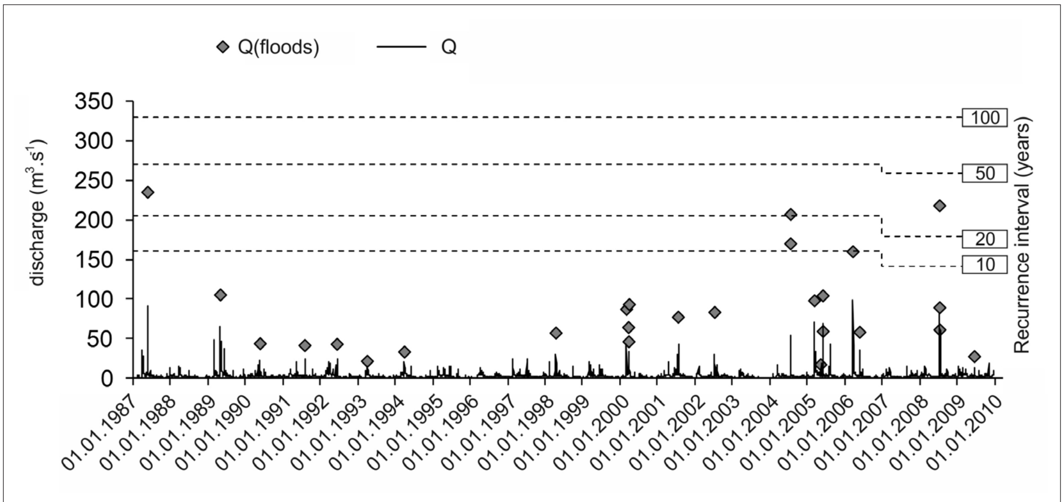

Fig. 2: Variability of daily average discharges (Q) in the period 1987–2009 on the Topľa River recorded at the Bardejov gauge station, discharge of flood events and recurrence interval over the same period
Source: Data (Slovak Hydrometeorological Institute); authors´ elaboration

Flood period	Area of erosion total [m²]	Area of deposition total [m²]	m²/year	
			erosion/year	deposition/year
1987–2002	318,047	424,204	21,203	28,280
2002–2009	534,063	176,951	76,295	25,279

Tab. 2: The area of erosion and deposition and the rate of erosion/deposition per year in the periods 1987–2002 and 2002–2009. Source: authors' calculations

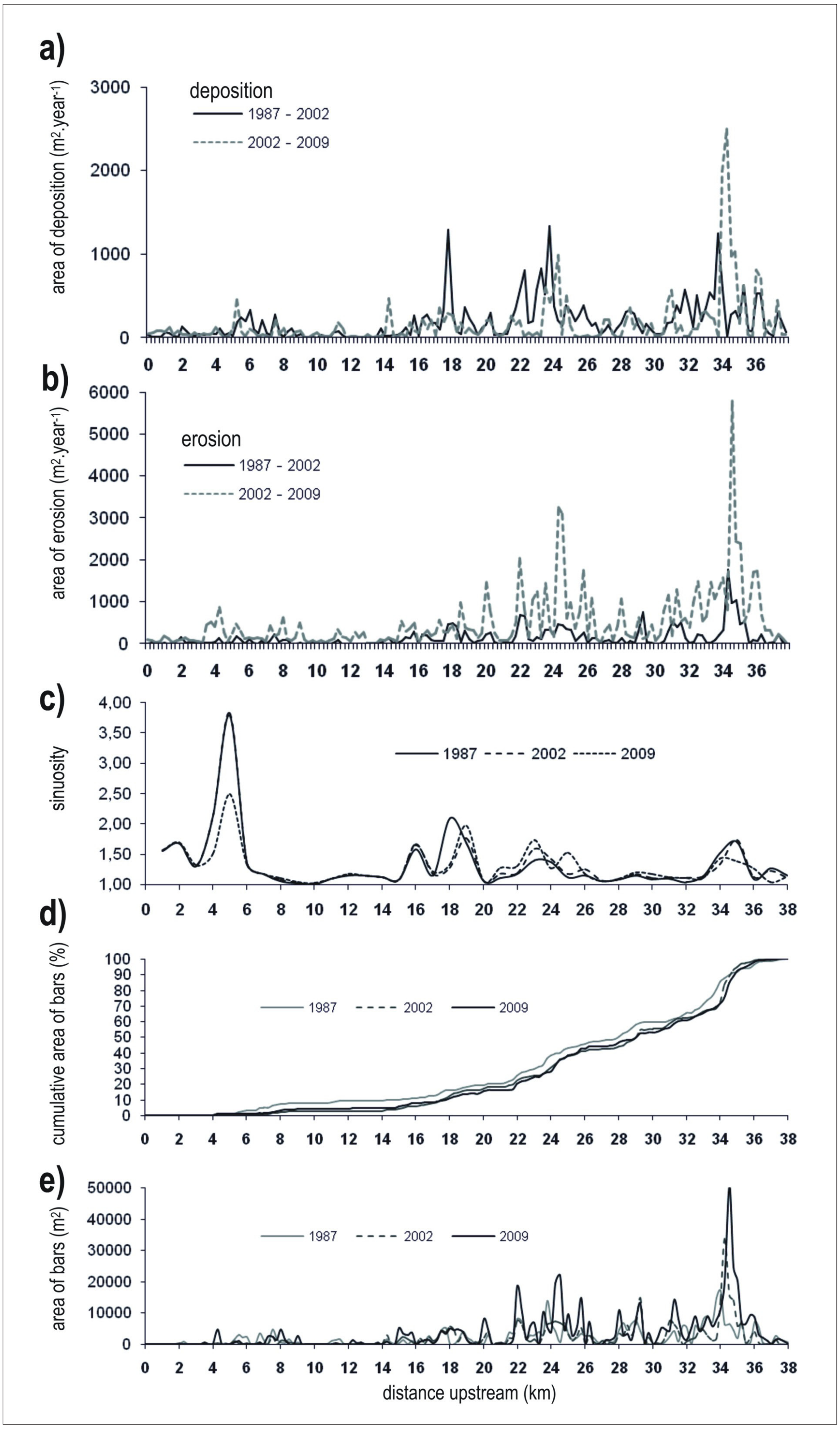

Fig. 3: Longitudinal evolution of (a) deposition, (b) erosion, (c) sinuosity, (d) cumulative area of bars, and (d) area of bars in the study reach of the Topľa River. Source: authors' calculations

The increase of erosion was particularly visible between 2002 and 2009. It increased up to 7.6 ha per year which is almost 3.6 times more than in the previous period (1987–2002). Reaches manifesting distinct instability of the channel were identified in the longitudinal direction (Fig. 3). The first and the smaller one (km 4–8) is linked with the system of meanders north of the town of Giraltovce (Fig. 4). Other similar locations are identifiable between the villages of Harhaj and Kučín (km 15–20), between kilometres 21–26 (in the cadastral territory of the villages Kurima and Dubinné) and north of the village of Hrabovec (km 30–36). They are linked to the reaches with a higher degree of sinuosity (Fig. 3c), where the planform pattern changed in the period 2002–2009.

The average channel shift in the study reach is 12.4 m (flood period 1987–2002) and 11.3 m (flood period 2002–2009) (Tab. 3). The average channel shift per year doubled from 0.8 m/year (1987–2002) to 1.6 m/year (2002–2009). A similar development is observable in bedforms where the area of gravel bars almost doubled in 2009. In 1987, they covered an area of 32.7 ha, which represented 26.9% of the overall channel area, and in 2002 they occupied a comparable area of 31.4 ha (28.2% of the channel area). Their representation increased in 2009 to 37.3% corresponding to an area of 54.8 ha. This phenomenon is most conspicuous north of Hrabovec (between kilometres 34 and 36), where the area of gravel bars increased from 5.7 ha in 1987 to 16.2 ha in 2009 (in 2002 the area was 9.7 ha) along the 2 km reach.

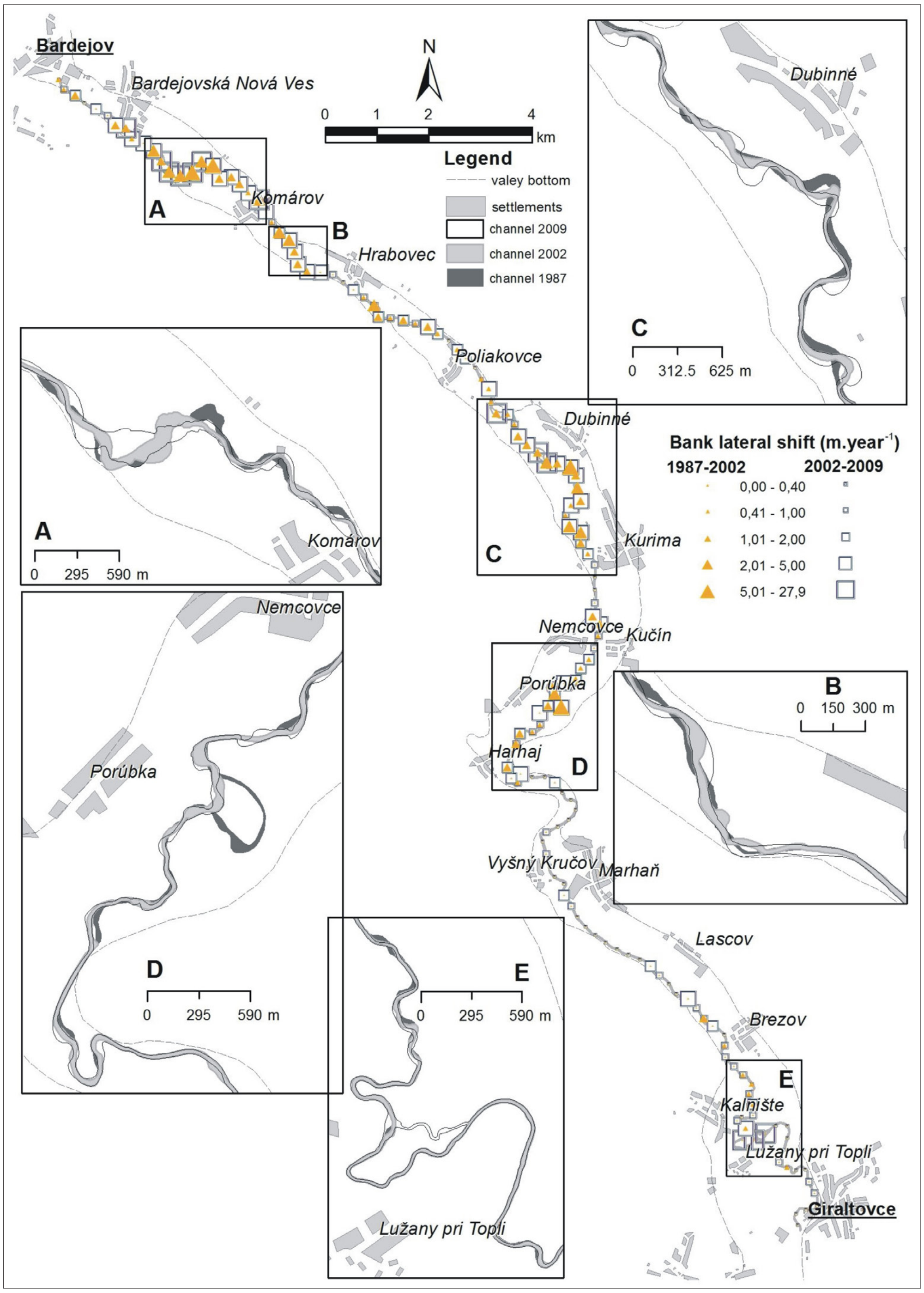

Fig. 4: The spatial distribution of lateral movements of bank line in the two study periods, and locations (A–E) with high lateral instability. Source: authors' calculations; Settlements layer (Geodesy, Cartography and Cadastre Authority of Slovak Republic (122-24-99-2012))

Flood period	Lateral shift [m]				Rate of shift [m.year^{-1}]		
	total	left bank	right bank	max. shift	total	left bank	right bank
1987–2002	12.4	11.4	13.5	260	0.8	0.8	0.9
2002–2009	11.3	10.7	12.0	445	1.6	1.5	1.7

Tab. 3: Lateral shift of banks and rate of shift per year in the periods 1987–2002 and 2002–2009
Source: authors' calculations

	Lateral bars		Point bars		Mid-channel bars		Islands		Σ
	[ha]	[%]	[ha]	[%]	[ha]	[%]	[ha]	[%]	[ha]
1987	22.8	69.8	6.7	20.5	3.2	9.7	0.0	0.0	32.7
2002	24.6	78.4	3.1	9.8	3.5	11.3	0.2	0.5	31.4
2009	39.7	72.5	9.0	16.4	4.0	7.3	2.1	3.9	54.8

Tab. 4: Changes in in-channel landforms of the Topľa River expressed by areas and percentage. The greatest intensity in bars changes and islands development was registered in 2009. Source: authors' calculations

The change of structure of individual gravel bars is negligible and is local (Tab. 4).

The most threatened reaches of the Topľa River are identifiable based on the average lateral bank shift in individual 250 m long segments (Fig. 4). The most dynamic reach is located south of the town of Bardejov, where the lateral shift reaches several hundreds of metres and threatens the wastewater treatment plant. The lateral shift also forms extensive gravel bars with the transition of the channel to a wandering river. Several dynamic reaches (located between Bardejov and Dubinné) are bound to points where water course transformation occurs from the abutted to the transversal (free) reaches. Three other very unstable reaches (Fig. 4: detail in C, D and E) are linked to the sinuous channel located in the centre of the valley characterised by typical chute offs and the formation of avulsive channels during floods.

4.3 Land cover changes in the riparian zone and bank erosion risk

Between 1987 and 2009, a total of 58.2 ha of riparian forest was eroded in the study reach (Tab. 5). The second most-eroded types of riparian landscape were arable land (19.4 ha) and grasslands and pastures (6.8 ha). The remaining two land cover types (shrubs and urbanised area) were only slightly affected by erosion. The erosion of forest, a result of their dominating representation in the delimited riparian zone, prevails in the reach. From an economic point of view, large destroyed farmland areas are a negative phenomenon (Fig. 5). The resulting damage in the area calculated according to Decree No. 38/2005 was € 29,924.02 in total; for the period 1987–2002 it was € 13,619, and in the period 2002–2009 it was € 16,304.33 This calculated value of destroyed areas does not reflect the real market prices of the land.

Erosion of built-up surfaces occurred in two places in the study reach of the Topľa. The first is erosion of part of a garden adjacent to an old homestead south of Hrabovec. The second is the destruction of a part of the wastewater treatment plant protective dike, located beyond the city of Bardejov, and disablement of the small hydropower station built in the meander bend (Fig. 6) due to its improper siting. The wastewater treatment plant was again threatened and the bank further eroded during the extreme flood of 2010.

Newly-formed deposition areas, which are created in the space of the old channel after its shifting by erosion, are progressively covered by natural succession. The result is a visible increase of the proportion of the riparian forest, which gradually replaces other eroded landscape structure types in the riparian zone (such as arable land or grassland): see Table 5.

5. Discussion

The channel's lateral shift, its width and the bedforms area of the reach studied, are affected by discharge in the short term, as they are controlled by the magnitude and frequency of floods and by the duration of low-stage periods. The increase of bank erosion after 2002 in the reach studied is obvious. In the first period, the rate of erosion and deposition were in approximate balance with

Flood period	Process	Land cover category [ha]				
		1	2	3	4	5
1987–2002	erosion	20.1	0.3	3.9	7.5	0.1
	deposition	40.9	0.3	1.2	0.0	0.0
2002–2009	erosion	38.1	0.5	2.9	11.9	0.1
	deposition	16.8	0.0	0.7	0.1	0.0

Tab. 5: Erosion of land cover categories in the riparian zone (ha) and the area of new land cover categories formed on the deposition areas after the lateral movement of the channel in the two study periods. Land cover categories: 1) riparian forest, 2) shrubs, 3) grassland and pastures, 4) arable land, 5) urbanised area.
Source: authors' calculations

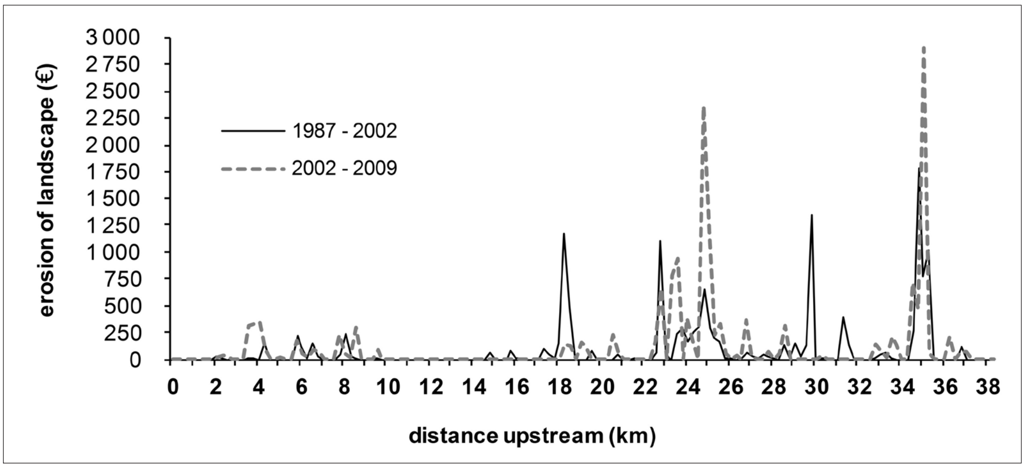

Fig. 5: Longitudinal evolution of the erosion of grassland, pastures and arable land in monetary terms (€)
Source: Authors' calculations

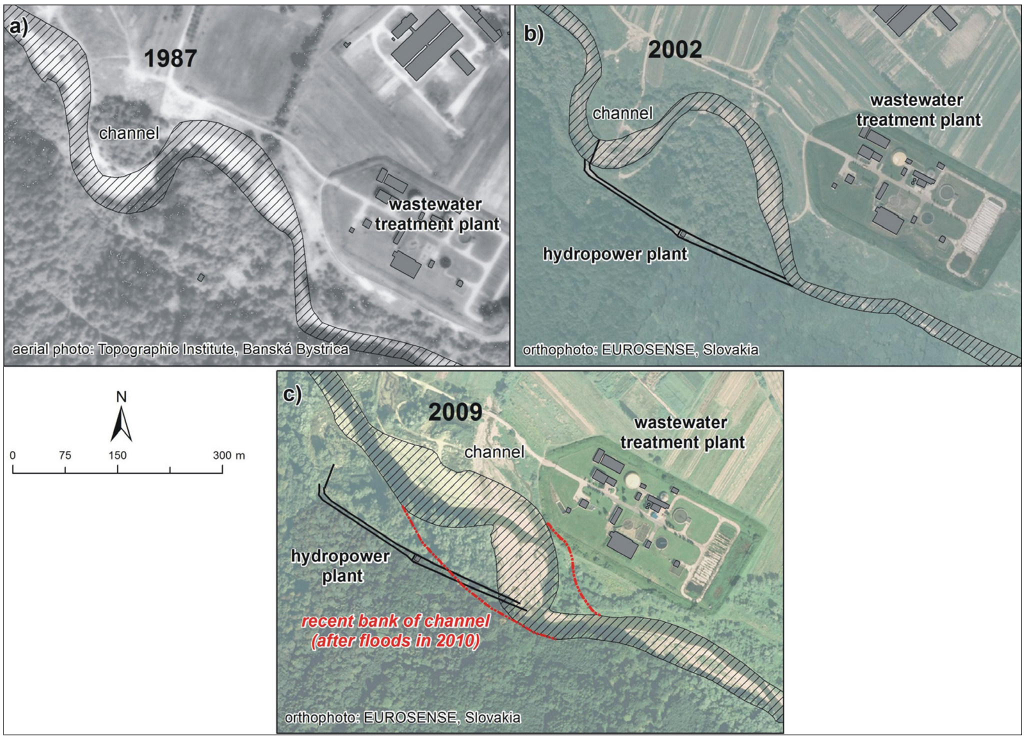

Fig. 6: a) Channel position in 1987; b) The channel position in 2002 with the small hydropower plant constructed in the meander loop in 2000; c) The changed channel planform in 2009 due to flood events in the second flood period leading to the dike's destruction close to the wastewater treatment plant, and the disablement of the hydropower plant as the consequence of its improper siting at the laterally active meander loop
Source: authors' elaboration; aerial photo (Topographic Institute, Banská Bystrica and EUROSENSE, Slovakia)

a slight prevalence of deposition. Due to the response of the river to the phase of low magnitude floods after events in 1987 and 1989, the channel narrowed from the average width of 31.4 m to 28.7 m and stabilised. Small discharges with a recurrence interval 1 or 2 years, which occurred in the reach between 1989 and 2000, did not exert larger destructive effects. On the contrary, in accord with Corenblit et al. (2007) and Phillips (2002), their effect was constructive and contributed to the stabilisation of the system. On the other hand, high magnitude and frequent floods after 2002 (and especially in 2004, 2006 and 2008) intensified erosion processes – the area of erosion compared to the area of deposition increased 3.6-fold and the average shift of the bank doubled. The result was widening of the channel to an average width of about 38 m.

Some authors (Bertoldi et al., 2009, or Hickin and Sichingabula, 1988) emphasise the predominant role of the channel-forming discharge or relatively smaller but long-duration floods in bank or floodplain erosion. As Lehotský et al. (2013) or Phillips (2002) point out, it is precisely the smaller discharge that leads to channel and planform formation and relatively slower bank erosion, which is connected with the overall behaviour of the river in the stage of dynamic equilibrium and hydraulic flow in the river bend (Hickin and Nanson, 1984). High magnitude floods lead to sudden and significant bank erosion, destruction of the planform and to partial or total rejuvenation of the stream, accompanied by channel and gravel bars expansion, and the destruction of old and formation of new stands for vegetation.

While bank erosion in bends is more or less continuous, its rate depends on the discharge régime. Therefore, channel shifting changes rhythmically; because of the lateral erosion, the channel widens and creates favourable conditions for the formation of large bar surfaces. This process is more pronounced if floods return frequently, enhancing bank erosion, and the stabilisation of the vegetation is limited. If years characterised by low discharges occur, however, the arboreous vegetation can stabilise the bar surfaces, leading to channel narrowing (Kiss and Blanka, 2012). Consequently, the changes in the characteristic stages and frequency of floods since 1987 can highly influence the long-term tendencies of channel migration and bedforms evolution. Individual landforms are formed and reformed in new locations, but they retain their generic identity as part of a landform assemblage. Thus, the Topľa as a meandering river is deemed to be "robust" if, over decades, it steadily migrates creating bars/point bars, which, in turn, are incorporated into a new floodplain, but yet retains its characteristic morphology of pools, riffles, undercut banks and bars/point bars. This can be described as "robust" behaviour within existing intrinsic thresholds, rather than "responsive" behaviour crossing extrinsic thresholds (Werritty and Leys, 2001). Not only does bank erosion lead to the development of new geomorphic diversity of a river, but it also provides several ecosystem services (Cebecauerová and Lehotský, 2012). Bank erosion may also have a psychological effect (Piégay et al., 1997).

The majority of eroded banks are located in less valuable places than settlements or arable land. The monetary expression of the damage caused by the bank erosion of arable land and pastures normally concern the unstable stretches (Fig. 7). The attention of water authorities or managers should focus precisely on these dynamic reaches, along with those where the stream directly threatens human activities. The calculated prices of eroded agricultural land reflect the prices set by Slovak law, which differ from those of the market. The actual market price of a plot of arable land in this area is two to three times higher. Ignorance of stream dynamics and behaviours often leads to the application of expensive and inappropriate interventions, which do not respect the natural development of the channel (Langhammer, 2010) (Fig. 8). An example of such inappropriate intervention is the location of the above-mentioned small hydropower plant. For a natural and healthy river state, the self-regulatory mechanism which leads to spontaneous self-organisation into a quasi-new balanced status is important.

Extreme discharges cause considerable bank erosion and the formation of new bar areas, which lead to a loss of arable land and the destruction of buildings. Bank failure occurrence indicates potential erosion in future years because they are not fixed by vegetation (Grešková and Lehotský, 2007), indeed even minor bank erosion related to the growth of channel loops leads to bank migration, but over a longer time frame.

6. Conclusions

Understanding the dynamics and behaviour of rivers in their natural environment and in the context of other components of landscape, makes it possible to predict the future development of the stream and its environs. It may simplify the co-existence of humans and the river and limit negative man-made interference with streams.

The Topľa River reach, as an unconfined gravel-bed river system, is typical for its migratory behaviour and obvious bank erosion. It is still one of the few minimally trained river reaches in the Slovak Republic and, therefore, ideal for contemporary monitoring of the dynamics of a river system. Gradual loss and bank destruction along the concave banks and deposition of material on the opposite

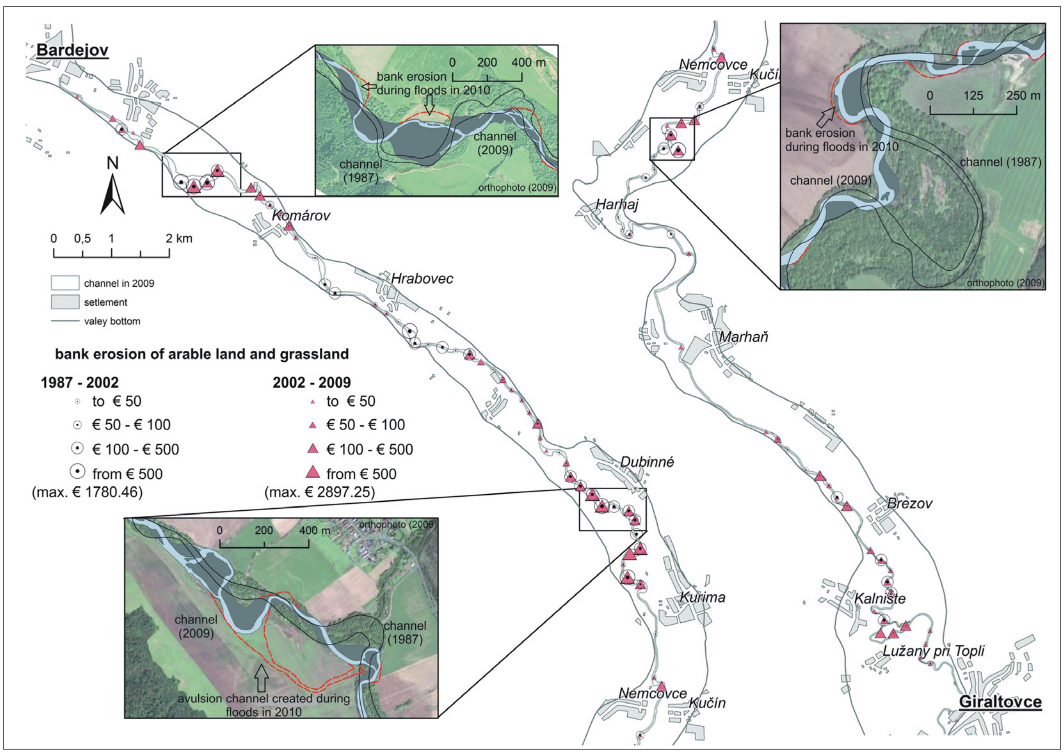

Fig. 7: Localities of grassland, pasture and arable land plots destroyed by bank erosion, and expressed by value (€) according to state-determined prices
Source: authors' elaboration; Settlements layer (Geodesy, Cartography and Cadastre Authority of Slovak Republic (122-24-99-2012)); aerial photo (EUROSENSE, Slovakia)

Fig. 8: An example of non-environmentally friendly river management. Channel lateral movement and bank erosion in the meander loop was stopped by the dike and the channel was shifted to the position before the flood event (left image). The inter-dike area close to the eroded bank was filled downstream by construction waste (right image). Despite these measures, channel migration continues. Photo: M. Rusnák

banks, are the processes that take place along the stream. The size of the shift itself is considerable – it moves about one metre per year and more than 10 m per year in the most dynamic reaches. The shift of the channel manifests itself by the formation of cutting banks and undercutting former floodplain and slope terraces. The channel shift is responsible for the change and destruction of the existing landforms and the deposition of new ones, followed by succession of vegetation and overall land cover changes in the riparian zone. Two different flood periods (1987–2002 and 2002–2009) with two different channel behaviours have been identified. The average channel shift per year doubled from 0.8 m/year (1987–2002) to 1.6 m/year (2002–2009). In total, an area of 85.2 ha was eroded and 60.1 ha was deposited. The most eroded land cover category in the riparian zone is floodplain forest, followed by arable land, grasslands and pastures and shrubs. From an economic point of view, the eroded floodplain with arable land and grassland (€ 29,924.02 in total) are negative consequences of channel migration. It is also necessary to bear in mind that channel migration and bank erosion are natural processes. A "green" approach is now preferred worldwide, one which avoids technical interventions into the channels and rivers are left to meander freely in certain areas (Piégay et al., 2005) or in certain reaches (Piégay et al., 1997). Piegay et al. (1997) also point out that active restrictive interventions in channels are expensive and result in a spiral effect leading to the degradation of streams and increased flood risk. Fortunately, the study river reach is a good example of a situation where the channel migration, bank erosion and bank destruction processes are not given much attention by local authorities.

Acknowledgments

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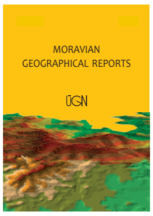

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An evaluation of soil retention potential as an important factor of water balance in the landscape

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Abstract

The ability of soil to retain water in its profile is one of the most important soil functions. It is expressed as the water storage capacity or retention capacity of the soil, and it is primarily affected by the physical properties of the soil. Given the fact that the direct measurement of hydrological data for the soil is very difficult in terms of capacity, statistically expressed pedotransfer functions (PTF) are currently used for the indirect estimation of hydrolimits. The data most commonly used for the PTF are easy-to-measure and usually readily available soil data on particle size, bulk density, organic carbon and morphometric parameters of the environment (e.g. slope of the relief, etc.). The listed pedotransfer functions are deficient for the complex evaluation of soil cover; given disagreements about the attributes, they cannot be directly used for the vector database of classified soil-ecological units in the Slovak Republic. Therefore, we have created a model of an algorithm from selected parameters compatible with the vector database of classified soil-ecological units, which also allows for the spatial distribution of the cumulative coefficient of water retention capacity (CWRC) for the soils of the SR. The results of this evaluation are presented using case studies of the areas of Levoča and Hriňová.

Key words: *water retention capacity, soil-ecological units, physical parameters, granularity, soil quality, relief morphometric parameters, Slovakia*

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1. Introduction

Soil is a crucial element affecting the overall capacity of landscape hydric potential. Its importance is understood not only for ensuring conditions for biomass production, but it is also a significant factor of ecosystem functioning and providing for the needs of human society. Soil functions have been defined from different perspectives by many renowned authors (Blum, 1990; Yaalon and Arnold, 2000; Bedrna, 2002; Loveland and Thompson, 2002). The EU Framework Directive on Soil Protection (European Commission, 2006) considers the ecological, socio-economic and cultural soil functions. These functions are biomass production, accumulation, filtration, transformation of nutrients, substances and water, carbon reservoir, reservoir of biodiversity, physical and cultural environment for anthropogenic activities, source of raw materials, and preservation of geological and archaeological heritage.

The importance of ecosystem evaluation is based mainly on economic and social values for society, and it is a result of a lack of appreciation of the dependence of society on the functioning ecosystem services, sources of biodiversity and the multifunctional nature of the resources used (Swanson and Barbier, 1992). The evaluation of environmental functions is always difficult and complicated as it considers inputs from many influences and factors. In terms of the needs of human society, however, the multi-functionality of soil has to be expressed in some way. Each soil function has to be assessed separately, as some of the functions are in mutual contradiction (e.g. retention and infiltration functions) (Bujnovský et al., 2009; Brodová, 2008).

Long-term research studies indicate which soil parameters are crucially dominant for the individual soil functions: physical characteristics are important for hydric functions, chemical soil parameters are important for ecological and stabilisation functions. The degradation-stabilisation function slightly depends on the majority of soil properties. In the assessment of the production potential mutual conditions are important, and they accumulate influences of all soil properties and parameters. Dominant among all soil characteristics is granularity, which affects all the other soil parameters.

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The ability of the soil to retain water in its profile is one of the most important soil functions. It is expressed as water storage capacity or the retention capacity of soil, and it is affected especially by soil physical properties. These are determined mainly by granularity, structure, soil depth and parameters of soil subtype. The soil retention potential is largely determined also by morphometric parameters of relief. Water storage capacity, together with infiltration rate, determine the resistance of the environment to surface runoff or water stagnation on the surface of soils after torrential or heavy rains. Both of these soil characteristics or functions contribute to the ability of the environment to withstand or to cope with floods, even though they actually influence each other in the opposite way: a high infiltration rate (observable particularly in sandy soils) generally means low water storage capacity, and high water storage capacity is typical for heavy soils with a low rate of natural infiltration. Thus, soils contribute to flood prevention and control either directly through the above-mentioned characteristics and functions, or indirectly through the co-influence with other elements and features of the environment.

2. Theoretical background

Retention capacity can be expressed by the hydrolimits of field capacity. Field capacity is a hydrolimit limiting the water content between gravitation and capillary water and corresponds to the pressure of 2.0–2.9 pF[1] (Antal, 1999). Given the fact that the direct measurement of soil hydrological parameters is very difficult in terms of capacity (Tietje and Tapkenhinrichs, 1993), statistically expressed pedotransfer functions (PTF) are currently used for the indirect estimation of hydrolimits. The apparent correlation between Θ(h), K(h)[2] and the content of individual soil grain-size fractions, led to the formulation of an empirical model – the so-called pedotransfer function (PTF) correlated to easily measured soil characteristics (granularity, specific weight, humus content, etc.) and hydrophysical soil characteristics (Gupta and Larson, 1979; Bouma, 1989; Pachepsky et al., 1996; Lamorski et al., 2008). The data most commonly used for the PTF are easy-to-measure and usually readily available soil data, usually particle size, bulk density and organic carbon, but also the morphometric parameters of the environment (relief, slope, climate, etc.). Most empirical regional PTFs for the territory of Slovakia use multiple linear regression models for the estimation of the hydrophysical parameters of soils, which estimate soil retention properties for selected components of the analytical equation of soil retention line (Šútor and Štekauerová, 1999; Houšková, 2000; Štekauterová et al., 2002).

The listed pedotransfer functions are deficient for the complex evaluation of soil cover due to disagreements about attributes, so that they cannot be directly used for the vector database of classified soil-ecological units of the Slovak Republic. Therefore, we have created a model algorithm from the selected parameters compatible with the vector database of classified soil-ecological units, which also allows the spatial distribution of the cumulative coefficient of water retention capacity (CWRC) for the soils of the Slovak Republic to be mapped. In this paper, we present possibilities for the interpretation of the selected parameters of the classified soil-ecological units in the quantification of water retention capacity of soils in the model areas of Levoča and Hriňová cadastres.

3. Material and methods

The process of developing an algorithm for the assessment of the water retention capacity of soils is presented in this section. We developed an algorithm for the quantification of water retention capacity of soils (WRC) using a suitable combination of the parameters of classified soil-ecological units (basic attributes of soil subtype, soil profile depth, granularity) and selected morphometric conditions of the environment (slope in combination with aspect).

The assessment of soil water retention capacity (WRC) was based on:

- the selected parameters of vector databases of classified soil-ecological units (M 1:10000) (NPPC, 2014) (Džatko, 2002) – granularity, soil profile depth and selected attributes of relief (slope); and
- a special purpose classification of soils of the Slovak Republic that determines the soil quality coefficient for individual soil subtypes in three basic granularity categories in the databases of classified soil-ecological units. Based on the assessment of production, buffering and retention soil functions, we determined the resulting cumulative coefficient of soil quality (for 336 soil units in three basic granularity categories occurring in the Slovak Republic – see Tab. 1)

The soil units assessed in terms of soil quality were the soil subtypes of the Morphogenetic classification system of the SR (VÚPOP, 2000) to which we added also the grain characteristics in three categories (clayey to loamy-clayey, loamy to sandy-loamy, loamy-sandy to sandy). In total, we reconsidered 336 soil units. The following Table 2 provides an example of the method of assessing the soil subtypes. The overall assessment of soil quality in the tabular input matrix was processed using factor analysis (FA) (Krnáčová and Krnáč, 1995). The input data matrix represented the database with 336 soil subtypes in 3 granular categories and with the evaluation of 3 ecological functions on a 5-degree scale. By the reassessment of the number of elements selected by the three ecological criteria on the 5-degree scale, we obtained 125 theoretically possible combinations. The determination of the final number of soil quality classes is based on the degree of similarity of the number combinations labelling the values of the environmental functions for the individual soil subtypes (Tab. 1). Quantification of the similarity of the values of the ecological functions is determined by the calculation of a correlation matrix generated from the input data matrix. According to the Malinowski error analysis, the next step determines the number of significant eigenvalues (or number of extracted factors), which means determining the number of soil quality classes with similar values of the ecological functions.

According to the interval of factor score values for the individual soil units and the given number of significant factors (number of associated soil quality classes), we have assigned each soil unit a final classification in quality classes. Table 1 shows an example of the final categorisation of soil quality according to environmental functions.

[1] pF = − log10 (cm)

[2] θ is the soil water content ($cm^3 \times cm^{-3}$); K is hydraulic conductivity ($cm \times day^{-1}$); h is soil water pressure head (cm)

3.1 Attribute characteristics of classified soil-ecological units

In terms of soil and ecology, the classified soil-ecological units are relatively the most homogenous units of the land evaluation information system. In fact, they represent the main soil-climatic units that are further divided according to the categories of their slope gradient, aspect, skeleton, soil depth and the granularity of the surface horizon. Each classified soil-ecological unit is identified and its soil-climatic properties are expressed by a combination of codes of individual properties at fixed positions in a 7-digit code.

Given the scope and chronology of mapping and evaluation of all agricultural soils in the SR, the soil database may include certain inaccuracies that need to be removed during the process of the Land Evaluation Information System update. Reasons of such inaccuracies were objective and subjective. Objective errors were caused by the inaccuracy of planimetry and by the elevation of base maps that result in the wrong determination of slope and aspect codes, but they are eliminated by using the digital model relief (DMR) generated from the focus of elevation in land consolidation

Soil types	Soil subtypes	Soil species	Value of trophic function	Value of buffer function	Value of accumalation function	Classes of quality soil
Lithic Leptosols		–	1	1	1	1
Skeletic Leptosols	Lithic Leptosols	I–IH	1	1	1	1
		H–PH	1	1	1	1
		HP–P	1	1	1	1
	Rendzi-Lithic Leptosols	I–IH	1	2	2	2
		H–PH	1	2	2	2
		HP–P	1	1	1	1
	Foli-Skeletic Leptosols	I–IH	2	2	2	3
		H–PH	2	2	2	3
		HP–P	1	1	1	1
	Skeletic (Skeli- Leptosols Dystric)	H–PH	2	3	3	5
		HP–P	2	2	2	3
	Cambi-Eutric Leptosols	I–IH	2	3	2	4
		H–PH	2	3	3	5
		HP–P	2	2	2	3
	Tephri-Skeletic Leptosols	I–IH	2	3	3	5
		H–PH	2	3	3	5
		HP–P	2	3	2	4
Eutric Regosols	Skeletic (Skeli-Dystric) Leptosols	I–IH	1	2	1	1
		H–PH	1	2	2	2
		HP–P	1	2	1	1
	Eutric Regosols Dystric	I–IH	1	2	2	2
		H–PH	2	2	2	3
		HP–P	1	1	1	1
	Calcaric Regosols	I–IH	2	3	2	4
		H–PH	2	3	3	5
		HP–P	2	3	2	4
	Eutric Regosols	I–IH	2	3	2	4
		H–PH	3	3	3	6
		HP – P	2	2	2	3
	Spodic Regosols	I–IH	1	1	1	1
		H–PH	2	1	2	2
		HP–P	1	1	1	1
	Stagnic Regosols	I–IH	1	1	1	1

Tab. 1: An example of the final categorisation of soil quality according to environmental functions. Notes: I-IH = clay-clay loam, H-PH = loam-sandy loam, HP-P = loam sandy-sandy. Source: Krnáčová, 2010

projects (LCP). Other inaccuracies arise as a result of human activities that significantly affect soil-forming processes (erosion, drainage, etc.) or completely change the initial configuration of the natural soil profile (reclamation, tillage, terracing, etc.). For these reasons, the Land Evaluation Information System was updated at a level of the soil-ecological unit classification system.

This update included a revision of basic pedological field research, in which changes occurred at the level of main soil units based on pedological probes and their morphological, chemical and physical analyses. Based on this update, the dial was innovated (main soil units were extended to a final number of 100, while a new 7-digit code was introduced into the classification of soil-ecological units, which includes soil-climatic characteristics expressed as a combination of the codes of individual characteristics at fixed positions of the resulting 7-digit code). The total number of classified soil-ecological units innovated by the Land Evaluation Information System generated more than 6500 codes (Linkeš et al., 1996).

3.2 Program-technical characteristics of the map database of classified soil-ecological units

The database is transformed into the universal vector format DXF and into the format of the environment of the program system GIS: ARC/INFO. It is thus usable by all types of GIS working with the DXF format.

Number of soil units (SU)	Real combination values of environmental functions				Coefficient of quality of soil units (CQSU)	Identification and description of soil class
1	1	1	1	1	1	Soils with very low trophism value, with a very small buffer system with very low accumulation capacity
	1	2	1	1		
	1	1	2	1		
	1	2	2	2	2	Soils with very low to low trophism value, with a very weak to weak buffer system and very low to low accumulation capacity
	2	2	1	2		
	2	1	2	2		
	2	2	2	3	3	Soils with low trophism value, with a weak buffer system with low accumulation capacity
	2	3	2	4	4	Soils with low to medium trophism value, a weak to moderately strong buffer system with low to moderate accumulation capacity
	2	2	3	4		
	3	2	2	4		
	2	4	2	5	5	Soils with low to medium trophism value, with a moderate-to-high buffer system with low to moderate accumulation capacity
	2	3	3	5		
	3	3	2	5		
	2	4	3	6	6	Soils with mean trophism value, with a moderate to high buffer system and medium to high accumulation capacity
	3	3	3	6		
	3	2	4	6		
	2	3	5	7	7	Soils with mean trophism value, with a moderate to high buffer system and moderate to very high accumulation capacity
	3	4	3	7		
	3	3	4	7		
	4	3	3	7		
	3	4	4	8	8	Soils intermediate with high trophism value, high buffer system, and medium to high accumulation capacity
	4	4	3	8		
	4	4	4	9	9	Soils with high trophism value, high to very high buffering system, and high accumulation capacity
	4	5	4	9		
	4	5	4	9		
	4	4	5	10	10	Soils with high trophism value, high to very high buffer system and very high accumulation capacity
	4	5	5	10		
336	5	5	5	11	11	Soils with very high trophism value, with very high buffer system, and very high accumulation capacity

Tab. 2: Coefficient of quality (CQSU) of soil units defined as an output of a special purpose SR soil classification
Source: Krnáčová, 2010

3.3 Interpretation of classified soil-ecological units

Creating the algorithm, we based it upon the pedotransfer rule. This is based on an assumption, which is also confirmed by direct measurements of pF values: the higher the clay fraction percentage in soil compared to the dust and especially the sand fraction, the higher the water storage capacity, and thus also the higher water retention capacity. It is similar for soil depth: the deeper the soil, the more water can be accumulated in its profile. Morphometric characteristics of the relief, namely slope, are also important in affecting the soil retention capacity.

This procedure can be written in the following logistic form:

$$CWRC_{soils} = \left[\left(CQSU_{1-1}\right)\cdot\left(G_{1-5}\right)\right]\cdot R_{\ 0-9}$$

where $CWRC_{soils}$ = Coefficient of soils water retention capacity, CQSU– = Coefficient quality of soil unit in SEU database, G = Category of soil granularity (clay content in %), and IR = Index of the relief (slope).

The output is a cumulative CWRC index by which we can review all the main mapping soil units regarding classified soil-ecological units in the Slovak Republic.

The range for the individual categories (0.1–11) is given by the results of the factor analysis (FA) and the number of 11 significant factor loadings that indicated the number of 11 soil quality classes out of 125 possible combinations of the selected ecological criteria. The range of intervals for individual categories of the cumulative CWRC index was divided into 10 categories in Table 3.

In order to evaluate the potential of soils to accumulate water, we selected the categorisation of water supplies derived from the field water capacity (FWC) (in mm). The above categorisation comes from the Bujnovský et al. (2009) study, where the FWC values ($cm^3 \times cm^3$) were aggregated by granular categories of the digital layer of classified soil-ecological units according to the individual soil-ecological regions. Thus, during the evaluation of soil retention capacity, also the spatial granularity distribution was taken into account. Subsequently, the values were recalculated according to the categorisation of classified soil-ecological units with respect to soil depth to the potential of their water accumulation in mm of water column (see examples given later for the case study areas, Tabs. 5 and 6).

3.4 Interpretation of selected attributes of classified soil-ecological units using the algorithm and their projection into the vector database of SEU polygons

The created algorithm (Tab. 4) was projected into the vector polygons of classified soil-ecological units (Fig. 1) for the example of the selected model area of the town of Hriňová, which is discussed in detail in the next section.

4. Results and discussion

4.1 The model area of the Hriňová town cadastre

The model area of Hriňová administratively belongs in the Banská Bystrica region and in the Detva district (the Hron River basin). A part of the cadastral area belongs in the Protected Landscape Area – Biosphere Reservation Poľana. The area is delimited by the cadastral border and covers the urban area of the municipality and adjacent meadow, pasture, arable land and forest areas. The vast forest complexes are dominant, especially at higher altitudes.

The diversity of relief, mineral substrates and the considerable humidity of the area determined the emergence and development of a specific spectrum of soils. The geological-relief conditions of the area, together with mainly climatic, hydrological and vegetation factors, also strongly differentiated the soil cover and its character.

CWRC category	Numerical designation of categories	Range of CWRC value
Very low	1	0.10–0.19
	2	0.20–2.28
Low	3	2.29–3.37
	4	3.38–4.56
Medium	5	4.57–5.55
	6	5.56–6.64
High	7	6.65–7.73
	8	7.74–8.82
Very high	9	8.83–9.91
	10	9.92–11.00

Tab. 3: Categories of cumulative CWRC index values
Source: authors' calculation

The model area – Hriňová										
Characteristic (SU)	Soil kinds	Code (G)	Code (SU)	Slope-degrees (SD)						
				0–1	1–3	3–7	7–12	12–17	17–25	>25
Dystric Cambisols on grandiorites (shallow)	Loam -sandy	1	76	3.1	3.1	3.(0.8)	3.(0.6)	3.(0.4)	3.(0.2)	3.(0.1)
Dystric Cambisols on grandiorites (shallow)	Loamy	2	76	5.1	5.1	5.(0.8)	5.(0.6)	5.(0.4)	5.(0.2)	5.(0.1)
Dystric Cambisols on grandiorites (shallow)	Loam -sandy	5	76	4.1	4.1	4.(0.8)	4.(0.6)	4.(0.4)	4.(0.2)	4.(0.1)
Dystric Cambisols on grandiorites (on the steep slope)	Loam- sandy	1	80	3.1	3.1	3.(0.8)	3.(0.6)	3.(0.4)	3.(0.2)	3.(0.1)
Dystric Cambisols on grandiorites (on the steep slope)	Loamy	2	80	5.1	5.1	5.(0.8)	5.(0.6)	5.(0.4)	5.(0.2)	5.(0.1)
Dystric Cambisols on grandiorites (on the steep slope)	Loam -sandy	5	80	4.1	4.1	4.(0.8)	4.(0.6)	4.(0.4)	4.(0.2)	4.(0.1)

Tab. 4: Algorithm of CWRC quantification (part of algorithm)
Legend: SU – main soil units, G – granularity. Source: authors' calculation

4.2 Retention capacity of the soil cover

Quaternary sediments in the form of gravelly fluvial sediments along watercourses conditioned the emergence of fluvial soils of modal and gley that are on cultivated soils anthropogenically altered into anthrosol fluvial soils. Anthrosol fluvial soils, loamy with values (CWRC 6.65–9.91) were included with soils of high and very high retention capacity. Gley loamy fluvial soils (CWRC 4.57–5.55) have medium retention capacity. Similarly, clayey-loamy types of fluvial soils are characterised by relatively good water retention, indicating that the soil is capable of storing quite a large quantity of water together with solutes in the soil profile. It should be noted, however, that with the increasing representation of a clay fraction in the soil profile, the water

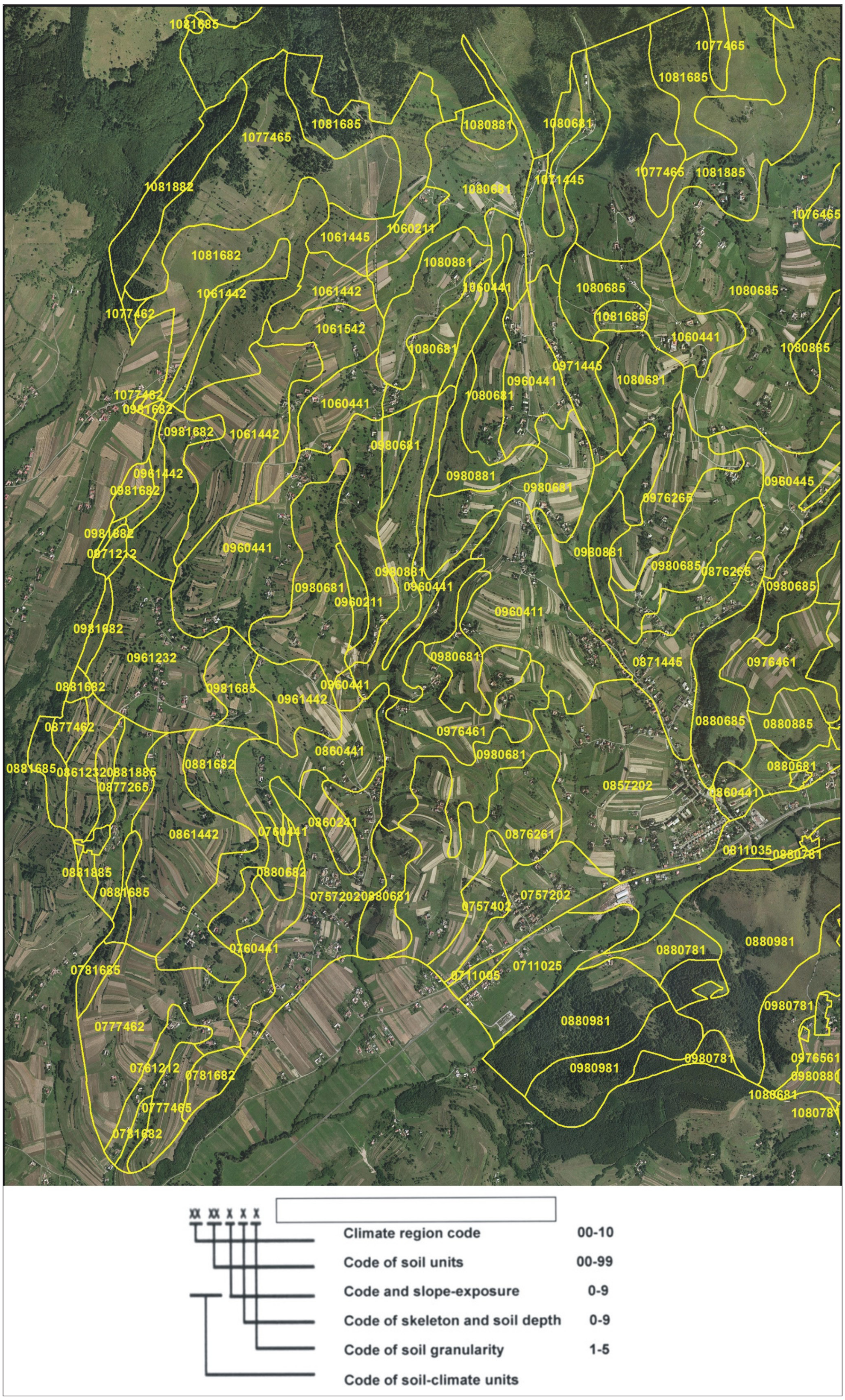


Fig: 1: SEU vector database (1:10,000) for the Hriňová model area storage capacity of soils (retention capacity) increases too, but so does the proportion of biologically unusable water. Hence, the landscape hydric potential increases, but the usability of the soil water for plants decreases.

The prevailing acidic rocks (grandiorites, biotic diorites, as well as volcanic rocks in the northern and northwestern parts of the territory) (Miklós, 2002) together with the forests, conditioned the emergence of modal cambisols that have been altered in the deforested areas by human agricultural activity into anthrosolic cambisols. Cambisols are the most common soil type in the examined area. They occupy nearly 90% of the land area. The agrarian landscape features a wide range of cambisols on diverse substrates.

Medium and higher values of water retention capacity (CWRC 4.57–6.64) were achieved by anthrosolic cambisols, deep and moderately deep, loamy on crystalline rocks, volcanic and other substrates. Their sandy-loamy varieties (CWRC 2.29–4.56) have lower water storage capacity, and thus also lower retention capacity. The southern part of the agrarian landscape features quite extensive occurrence of anthrosolic pseudogley on loess loams. Loamy types have a high WRC (CWRC 5.55–6.64). Pseudogley on polygenic loams, loamy, had lower values falling within the CWRC interval 3.37–4.56.

Only a small part of the territory at the southern border of the cadastre is covered by anthrosolic rendzinas bound to more basic geological substrate with medium to high WRC values (CWRC 4.46–6.64). These are soils with a high proportion of quality organic substances; however, the high proportion of skeleton in their soil profile reduces the total water storage capacity and thus also the WRC. Organosols occur occasionally too. Organosols are characterised by the deep peat horizon with high accumulation of organic substances. In terms of retention, organosols represent an important water reservoir in the landscape. Their CWRC values ranged from 8.82 to 9.91, i.e. soils with high to very high retention capacity.

The area outside continuous forests in the cultivated landscape, features light sandy to loamy-sandy soils, sometimes even moderately heavy loamy to sandy-loamy soils. The soils are predominantly medium-skeletal, only locally strongly skeletal. It follows that given the prevailing occurrence of cambisols with a smaller proportion of clayey fractions, we can include the hydric soil potential into the category of low retention capacity (Fig. 2). The overview of surface area actually occurring in the soil WRC category is presented in Table 5.

Land use and management are very important in terms of total landscape hydric potential. In terms of land use in 2010, the largest share of the cadastral area was taken by forest elements and semi-natural sites, which accounted for 72%

Categories of water retention capacity (WRC)	Degrees of water retention capacity (WRC)	Area (m^2)	Area (%)	Categories of water resources (derived from FWC)
Very Low	1	4,314,640.54	11.49	≤ 100 mm
	2	14,623,637.84	38.94	
Low	3	10,019,588.83	26.68	101–200 mm
	4	6,477,937.38	17.25	
Moderate	5	2,114,911.23	5.63	201–300 mm

Tab. 5: Areas of the currently occurring WRC soil categories (Hriňová). Legend: FWC – categorisation of water resources derived from the full water capacity of water level height in the soil profile. Source: authors' calculation

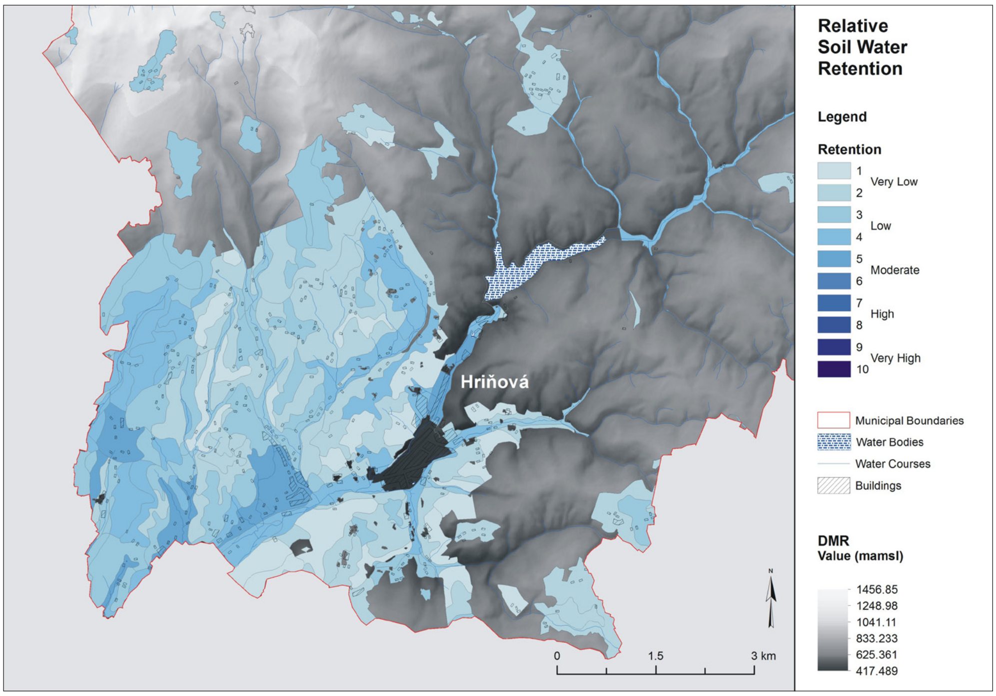


Fig. 2: WRC of soil cover in the Hriňová model area. Source: authors' elaboration

of the area (9,143.65 ha) (Mojsej and Petrovič, 2013). The second largest group in the current landscape structure was represented by agricultural land elements, which accounted for nearly Ľ of the cadastral area (23.53% – 2,974.81 ha). The greatest part of the agricultural land was localised in the SW part of the area. The largest area consisted of a mosaic of arable land with permanent grasslands (with non-forest woody vegetation up to 20%) (Petrovič and Mojsej, 2011).

The mosaics of arable land and grasslands create important eco-stabilising, soil-protecting and hydric-effective elements in the landscape. Stabilisation, revitalisation and respect for the principles of sustainable management may lead to a more balanced hydrological cycle in the landscape (Antal et al., 1989).

4.3 Retention capacity of the soil cover in the Levoča town cadastre

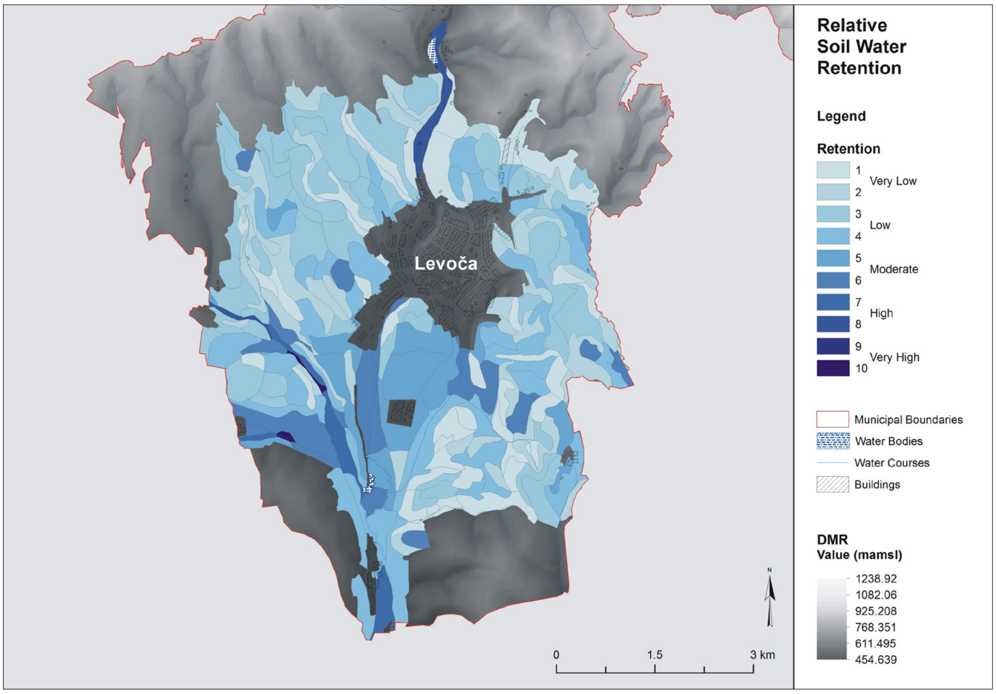
The geological base consists of sandstone and shale strata widespread in the peripheral parts of the Levoča Mountains. Alternating are massive sandstone benches (thickness 30–150 cm) with calcareous shales on the southern and western margin of the mountains (Gross, 1999). Soils are predominantly saturated modal cambisols, loamy to sandy-loamy. The water retention capacity of these soil complexes reaches in terms of their parameters a relatively moderate value within the CWRC interval 5.55–6.64. The dominant part of the landscape relief consists of hilly relief, moderately to strongly ragged on deluvial sediments with the prevailing occurrence of anthrosolic cambisols, loamy, in complexes on more basic substrates with pararendzinas. Their value ranges from 5.56 to 7.73, which is a medium CWRC value. In the western and northwestern parts of the area, shallow cambisols developed on flysch substrates, loamy to clayey-loamy with a low value of water retention capacity in the CWRC range from 2.29 to 3.37. Shallow cambisols on flysch substrates occupy quite large areas in this part of the area and their retention capacity is low. They are intensively agriculturally used and unthrifty use and poor agronomic management can lead to increasing surface runoff and increased water erosion. On more defined slopes, regosols developed locally, strongly skeletal, loamy and sandy-loamy, whose CWRC is 0.20–2.28. These soils have a very low retention capacity, and therefore the use and management of the landscape are crucial. They are usually used as extensive meadows and pastures, which optimises the hydrological regime of the landscape.

Fluvial sediments along watercourses consist of pebbles, sands and silty loams, on which a fairly wide range of fluvial soils developed. In the southern part of the area, in the basin of Levoča River tributaries, there are anthrosolic fluvial soils, clayey-loamy. Their water storage capacity with respect to optimum physical parameters reaches relatively the highest CWRC values in the area, in the range 6.64–7.73.

A relatively high retention capacity is also achieved by carbonate fluvial soils, clayey-loamy in the basin of the Levoča R., in the southern part of the territory. Gley fluvial soils of moderate to heavy weight with respect to the high groundwater level in the soil profile exhibit a relatively lower water storage capacity that ranges from 5.55 to 6.64. The locally-present rendzinas on carbonate, loamy to clayey-loamy substrates, are characterised by medium CWRC values ranging within the interval 4.57–6.64.

On more defined slopes of carbonate rocks, shallow rendzinas developed, usually strongly skeletal, clayey-loams with the relatively lowest water storage capacity (CWRC 0.20–3.37). An overview of areas of soil WRC categories can be seen in Table 6 and their spatial representation is shown in Figure 3.

With regard to the localities with more ragged and sloping relief in the evaluated area, where the soil cover reaches lower CWRC values, agricultural management is very important. In the cadastral area of the Levoča town with an acreage of 6,404 hectares, agricultural land represents 3,226 ha (57.37%), of which 1,752 ha (27.35%) is arable land, 1,263 ha (19.72%) are pastures and meadows,



Tab. 6: Areas of the curently occurring WRC soil categories (Levoča). Legend: FWC – categorisation of water resources derived from the full water capacity of water level height in the soil profile
Source: authors' calculation

Categories of water retention capacity (WRC)	Degrees of water retention capacity (WRC)	Area (m^2)	Area (%)	Categories of water resources (derived from FWC)
Very low	1	4,698,761.88	15.60	≤ 100 mm
	2	4,549,070.60	15.10	
Low	3	8,137,923.78	27.01	101–200 mm
	4	6,213,347.43	20.62	
Moderate	5	2,866,672.72	9.52	201–300 mm
	6	2,539,433.03	8.43	
High	7	624,046.27	2.07	301–400 mm
	8	429,493.79	1.43	
Very High	10	61,452.87	0.20	> 400 mm

Fig. 3: WRC of soil cover in the Levoča model area. Source: authors' elaboration

and forest land represents 2,544 ha (39.72%). Sound agronomic procedures applied on arable land and a relatively high proportion of permanent grasslands create good soil-protecting conditions, which determines a more balanced hydrological cycle in the landscape.

4.4 General comparison of results from the two studied territories

The overall retention capacity of the model territories can be compared in terms of the calculated areas for the individual RWC categories. The model territory of Levoča has more extensive areas of cultisolic loamy cambisols in the medium RWC category, representing 18% of the total area of agricultural land (PPF), as compared with the Hriňová model territory, where this category makes up only 5.6% of the area. The representation of very low to low soil RWC category is 31% and 47% in the Levoča area, in comparison with the Hriňová area, where these categories represent 50% and 44%. The overall quite high representation of soils with low retention capacity in both areas is determined by the geomorphology of the area. The soils with medium and higher retention capacity in both model areas consist of loamy fluvisols in the floodplains of local watercourses and, in the Hriňová area, cambisols on volcanic substrates.

5. Summary of the international science in pedotransfer functions (PTF)

Research on predictive functions that derive soil properties that are difficult or expensive to measure from easily or routinely measured soil properties, is on the rise. Bouma (1989) introduced the term ‘pedotransfer function’ (PTF) for such predictive functions. Recently published reviews on PTF development and use include those of Pachepsky et al. (1999), Wősten et al. (2001) and Pachepsky and Rawls (2005). Databases of different sizes, scales and detail are available to develop PTFs that predict soil hydraulic properties; see Wősten et al. (2001). Many studies compare and/or validate the performance of different PTFs. Recent publications on the issue include those of Kern (1995), Tietje and Hennings (1996), Schaap and Leij (1998), Imam et al. (1999), Cornelis et al. (2001), Wagner et al. (2001), and Minasny and McBratney (2002). Some studies go further and evaluate the functionality of PTFs (e.g. Wősten et al., 1999; Hack-ten Broeke and Hegmans, 1996; van Alphen et al., 2001; Nemes et al., 2003; Soet and Stricker, 2003). Studies that belong in the first group evaluate how well certain functions predict water retention (or hydraulic conductivity), whereas the second group of studies evaluates the performance of predicted soil hydraulic characteristics through the simulation of some practical aspects of soil behaviour.

A major obstacle to the wider application of water simulation models is the lack of readily accessible and representative soil hydraulic properties. To overcome this apparent lack of data, a project was initiated to bring together hydraulic data on soils available from different institutions in Europe into one central database. This information was used to derive a set of pedotransfer functions that can provide a satisfactory alternative to the costly and time-consuming direct measurements.

A total of 20 institutions from 12 European countries collaborated in establishing the database of Hydraulic Properties of European Soils (HYPRES). As a consequence, it was necessary to standardise both the particle size and the hydraulic data. Standardisation of hydraulic data was achieved by fitting the Mualem-van Genuchten model parameters to the individual θ(h) and K(h) hydraulic properties stored in HYPRES.

The HYPRES database contains information on a total of 5,521 soil horizons. Each soil horizon was allocated to one of 11 possible soil textural/pedological classes derived from 6 FAO texture classes (5 mineral and 1 organic) and two pedological classes (topsoil and subsoil) recognised within the 1:1,000,000 Soil Geographical Database of Eurasia. Then, both class and continuous pedotransfer functions were developed. The class pedotransfer functions were used in combination with the 1:1,000,000 Soil Database of Europe in order to determine the spatial distribution of soil water availability (Wösten, 1999).

Scenario studies are important in planning for various hazards and their prevention. Field experiments representing different management possibilities would be time consuming, costly and sometimes even risky. Exploratory (‘what if?’) modelling offers an alternative that is quicker and easier to execute, and may give at least indicative answers about trends that are expected to occur. Well-tested PTFs can assist and enhance such modelling, as they can provide low-cost and low-risk input data without the need to run experiments that may cause changes to our environment. Possibilities to compare such simulations with (field) measurements are limited, so one has to be careful with the interpretation of results.

Land use is in many ways related to the amount and quality of water, biodiversity and the provision of ecosystem services. Climate change puts emphasis on soil as a particularly vulnerable resource. Soil functions including soil stability, the water cycle in the soil, balancing the amounts of nutrients and biotic integrity, are important parameters of soil fertility. Thanks to the function of carbon sequestration, soil plays a key role in mitigating climate change. Appropriate management of the soil has to prevent its degradation and erosion, to stabilise its functions and to take into account the mitigation of climate change consequences and adaptation to the climate change. The model presented in the RWC study of soil can significantly contribute to increase the quality of the methodology of land reform projects, which is in the process of development, as pointed out by Muchová et al. (2016).

6. Conclusion

Soil water retention capacity represents an important hydrolimit determining and affecting many other soil characteristics and functions. Natural soil retention ability represents a significant part of the mosaic of individual components of the environment and highlights the potential risk areas, regarding floods, as well as areas where this risk can be eliminated to some extent by suitable land use and landscape management. Using the parameters of the databases of classified soil-ecological units to determine WRC enables a relatively easy identification of the amount of water potentially held in agricultural soils of Slovakia. Human activity that affects soil retention capacity or the rate of water infiltration into the soil, also affects the ability of the landscape to react to the flood threat. An increase of the retention ability of the landscape is one of the basic conditions for lasting and sustainable development and the protection of water resources. It is expected that in the Slovak Republic, the current imbalance in rainfall distribution will increase in terms of time and space, which will lead to stronger effects of extreme precipitation and droughts. Therefore, the increase of water retention in the landscape is one of the primary tasks of water management, which can largely mitigate the negative effects of climatic changes, such as the decrease of groundwater resources. The objective of proper land use, and thus also its individual components, should be to preserve their mutual balance that would integrally contribute to the beneficial use of land and water resources. This would significantly eliminate the risk of flood occurrence and the landscape should have a high capacity to quickly deal with the consequences of possible floods.

Acknowledgement

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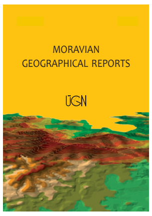

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Planning a greenway based on an evaluation of visual landscape attractiveness

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Abstract

The potential for using a standardized landscape evaluation method for planning a greenway in a young glacial area in northern Poland is evaluated in this paper. In the evaluation of visual landscape attractiveness (VLA), we took into account not only its natural but also its cultural components. The cultural components were divided into two groups, i.e. increasing and decreasing VLA scores. The sources of data needed for the evaluation included a Vector Smart Map level 2 (VMap L2), aerial photographs and a field survey. The newly-designated greenway links two landscape parks (which play the role of greenspaces) and runs along numerous lakes, forests, rivers, and objects of cultural heritage. The greenway is composed of existing local roads, allowing a more optimal utilisation of natural and cultural resources of the landscape, primarily those located between the selected greenspaces. Using this application, the idea of sustainable development can be implemented, and the overlapping protected areas will not be subject to devitalisation. The VLA method can facilitate multiple greenway designations in other areas.

Keywords: *landscape quality, visual landscape attractiveness, greenway, GIS, Poland*

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1. Introduction

Landscape quality assessment is a complicated procedure involving many senses and quantification of all aspects of the landscape, not only natural and cultural (including infrastructure) but also perceptual, e.g. landscapes as national heritage (Visual Resource Management Program, 1980; Rogge et al., 2007; Mouflis et al., 2008; Tempesta, 2010; Sevenant and Antrop, 2010; Conrad et al., 2011; Pettit et al., 2011; Svobodova et al., 2012; Best Management Practices…, 2013; Skokanová, 2013; Špulerová et al., 2013; Tempesta et al., 2014; Van der Wal et al., 2014). Here we focus on one component of landscape evaluation – visual landscape attractiveness. It is regarded as the most important factor of the multisensory landscape (Bell, 2004). Humans evaluate landscape primarily on the basis of visual inspection, and most frequently visual evaluation determines our perception of the surroundings.

The European Landscape Convention (Council of Europe, 2000), draws attention to the need to assess landscapes, taking into account the particular values assigned to them and to define landscape quality objectives for the landscapes. One of the possible methods of landscape assessment is the evaluation of visual landscape attractiveness (Degórski et al., 2014).

The concept of greenways, sometimes referred to as trails for the 21st century (Flink et al., 2001), is poorly known among geographers in Central and Eastern Europe. The greenway concept is compared with the European vision of ecological corridors (Fabos and Ryan, 2004). Greenways, however, are supposed to serve people who need contact with nature and culture (President's Commission, 1987), while the major role of ecological corridors is to create favourable conditions for genetic exchange of fauna and flora between core areas (Perzanowska et al., 2005).

The origin of greenway planning goes back to the beginning of the landscape architecture profession in the USA (Fábos, 2004). One of its tasks was to designate greenways that link enclaves of attractive landscape, i.e. greenspaces (Fig. 1) – where people can get in touch with their cultural heritage – and urban open spaces (Zube, 1995). The idea to create greenways had evolved from a system of parkways, which connect urban and rural areas. The

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precursor of this concept is supposedly due to Frederick Law Olmsted, who designed the famous Boston Park System (Little, 1990). In the second half of the 20th century, the greenway concept has been transformed into an approach based on sustainable development and the stimulation of physical activity (European Greenway Association, 2014). Despite the passing years, however, the roles of greenway and greenspace remain the same – they should for example limit the defragmentation of green areas and create attractive transportation routes to link them. According to the European Greenways Association, greenways should be transportation routes and meet standardized criteria for their planning (e.g. Greenway Polska Society, 2015). Within cities, corridors between parks are designed (Fábos, 2004; Tan, 2006; Teng et al., 2011), while on the national or regional scale, greenways are found between national parks and landscape parks.

In the literature on this subject, several types of greenways can be distinguished, referring to their function (Viles, Rosier, 2001; Fábos, 2004):

- ecologically significant natural corridors between natural systems;
- recreational greenways (often along watercourses); and
- greenways that provide historical heritage and cultural values.

The procedures for greenway planning can be divided into several steps (modified from Fábos, 2004):

- Step 1: Research and map all existing trails, roads, protected areas and other objects of importance for ecological/nature protection, recreational and historic/cultural values;
- Step 2: Research and map all current planning proposals relevant to the three categories above (ecological/nature protection, recreational and historic/cultural values);
- Step 3: Make connections for each category of greenways at each level;
- Step 4: Determine the dominant function of the planned greenway and create single-purpose plans for nature protection, recreation, historical/cultural resources; and
- Step 5: Create a greenway plan, which integrates all existing, current and proposed plans of trails, etc., and provide statistics of the new greenway.

2. Aim of the study

The fast development of the road network and infrastructure in recent years in Poland, inspired us to attempt to design a greenway between two landscape parks: Brodnica Landscape Park (Brodnicki Park Krajobrazowy), and Górzno-Lidzbark Landscape Park (Górznieńsko-Lidzbarski Park Krajobrazowy) in Northern Poland. We aimed to plan the greenway so that it would be characterised by a high landscape value and connected with the rich tradition and history of the region (Zube, 1995). We assumed that although greenways are intended for use by non-motorised tourists, in practice exceptions to this rule are possible. Also, according to the European Greenways Association, it is permissible to share the greenway with light motor traffic. The benefits of such a solution are confirmed by the results of research on the use of existing roads in the creation of greenways in New Zealand (Viles and Rosier, 2001). In our study, we also used the current road network in planning the greenway, assuming that its basic function related to local motor traffic will be maintained.

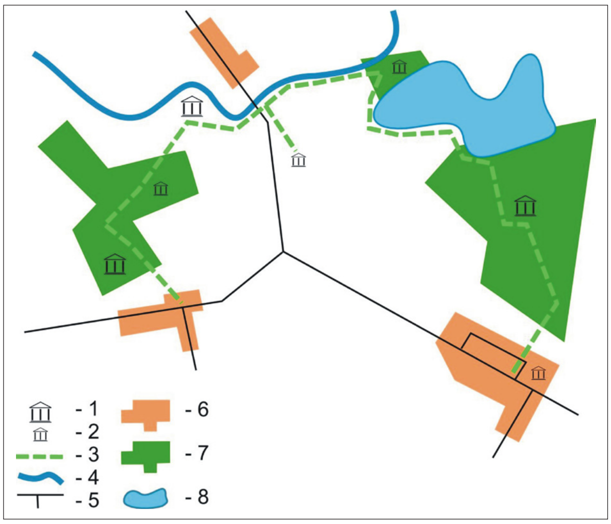

Fig. 1: The current concept of designating greenways
Legend: 1 – primary object of cultural heritage; 2 – secondary object of cultural heritage; 3 – greenway; 4 – rivers; 5 – existing main roads; 6 – built-up areas; 7 – greenspace, e.g. a landscape park; 8 – water body
Source: authors' conceptualisation

Local greenways should start in places with a well-developed road and tourism infrastructure (European Greenway Association, 2014). Brodnica and Górzno, as towns with well-developed tourism and the headquarters of landscape parks, undoubtedly have such an infrastructure. Planning of a completely new route was not considered, because of the already relatively high density of the road network in the region (1.31 km/km^2), partly to avoid further fragmentation of green areas. To designate the greenway, as reported earlier by Garré et al. (2009), we selected paved roads characterised by light traffic to allow comfortable travel and limit the cost of adapting the road to perform new functions.

3. Study area

For this study, we selected an area of 1,402.25 km^2 (Fig. 2), located at the juncture of three provinces in Northern Poland: Kujawsko-Pomorskie (in Brodnica and Rypin Counties), Warmia-Mazury (in Nowe Miasto Lubawskie, Iława, and Działdowo Counties), and Masovia (in Żuromin County).

The study area includes parts of four historical regions: Chełmno Land, Dobrzyń Land, Michałowo Land, and Lubawa Land. After the partitions of Poland (i.e. in 1795), the south-eastern part of the study area was crossed by the border between Prussia and Russia. After World War I, the whole study area was within the 2nd Republic of Poland, but the border between Poland and Germany (East Prussia) was situated north of it. Because of the changing borders between countries and the many battles that took place in the study area, it has a very rich history, but, as a result, a relatively small number of historical buildings still exist, and some of them are in poor condition.

According to the physico-geographical division of Poland (Kondracki, 2009), the study area is within the macroregion of Chełmno-Dobrzyń Lakeland (Pojezierze Chełmińsko-Dobrzyńskie), primarily in the mesoregions of Lubawa Hump (Garb Lubawski, 33.3%), Brodnica Lakeland (Pojezierze Brodnickie, 27.2%), and Drwęca Valley (Dolina Drwęcy, 17.4%), with only small parts in Górzno Plain (Równina Górznieńska, 6.9%) and Iława Lakeland

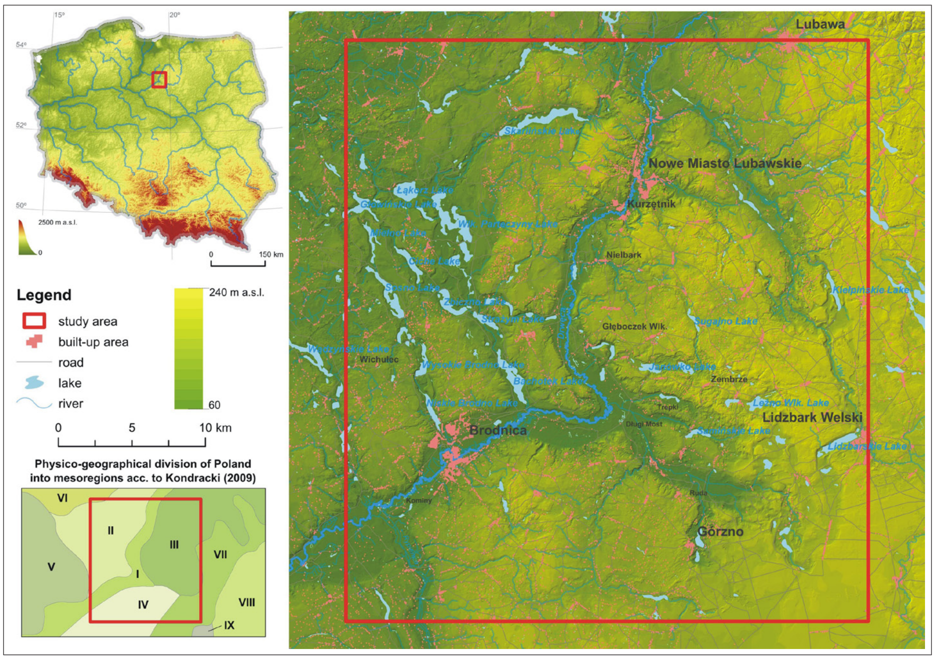

Fig. 2: Location of the study area in a hypsometric map. Legend: I – Drwęca Valley; II – Brodnica Lakeland; III – Lubawa Hump; IV – Dobrzyń Lakeland; V – Chełmno Lakeland; VI – Iława Lakeland; VII – Urszulewska Lowland; VIII – Mława Hills; IX – Raciąż Lowland. Source: authors´ elaboration

(Pojezierze Iławskie, 0.3%). The most elevated part is on the Lubawa Hump, at an altitude of 192 m (in the north-eastern part of the study area), while the lowest place is in the Drwęca Valley at an altitude of 65 m (in the south-western part of the study area).

Land relief has been shaped chiefly by erosion and accumulation related to the ice sheet and its meltwaters during the last glaciation (Vistulian) about 17,000 to 16,000 years BP. In that period, glacial forms (flat and undulating moraine plateaus, terminal moraines), as well as fluvioglacial forms (e.g. sandurs, meltwater channels) have been shaped. They were transformed in the late Pleistocene, in periglacial conditions. Then, periglacial denudation valleys were created, and during the warmer phases the dead ice melted and the resultant kettle holes were transformed into kettle lakes. After the arrival of Neolithic settlers, who introduced agriculture and pastoralism, anthropogenic denudation was initiated as a result of forest clearance and tillage.

In the Brodnica Lakeland, near the village of Wichulec, a chain of morainic forms is visible in the land relief, extending to Zembrze and Wielkie Leźno. The moraine plateaus are slightly undulated and dissected by numerous subglacial channels (up to 50 m deep). The subglacial channels, currently used by the watercourses of Struga Brodnicka, Skarlanka, and Rypienica, are up to about 0.5 km wide. The Drwęca valley is the widest (1–3 km), running from the NE to SW. Close to it, near the village of Kurzętnik, the greatest differences in altitude (over 100 m) are observed.

In the current land relief, some landforms result from economic activity, including excavation of gravel or other construction aggregates. The largest excavation pits are located in the Drwęca Valley (near the villages of Nielbark and Długi Most) and are partly flooded. Abandoned pits are also found near the villages of Ruda, Głęboczek Wielki, and Kominy. Some of the excavation sites have been rehabilitated and designated for afforestation or development. In the study area, apart from construction aggregates, lacustrine tufa was also extracted, e.g. in Trebki and Janówko, as well as clays and peat. Moreover, currently gravel and sand are often extracted from small pits, which are not rehabilitated afterwards.

Because of the varied relief and large differences in altitude, road construction has led to the creation of many embankments, roadside ditches, excavation, trimming, and levelling. Anthropogenic landforms also include grading plains and levelled areas in housing estates, as well as remnants of small medieval settlements, which are relatively rare. Some other anthropogenic landforms result from water resource management: drainage and irrigation ditches, embankments of reservoirs, the basins of mill ponds, mill streams (leats), etc. The landscape is only to a small degree affected by anthropogenic forms resulting from agrotechnical denudation (mostly due to ploughing) and natural slope processes activated by many years of tillage. The forms related to farming activity include high borders between fields (usually grassy), soil-slope aggradation cones from arable fields, areas degraded by farming activity, aggradation covers, grading plains and levelled areas in farmlands. The land relief has been transformed by human activity in only about 4% of the study area in total, however, and the transformed sites are associated primarily with human settlements and transportation (Podgórski, 1996).

A large part of the study area is covered by landscape parks (LPs, Fig. 3): Brodnica LP (166.85 km^2) and Górzno-Lidzbark LP (227.64 km^2). Brodnica LP was created in 1985. A relatively high proportion of the park area is covered by lakes (10%) and over 60% by forests, primarily pine-dominated and mixed forests on sandy acidic soils. Alluvial forests and alder carr forests occupy only a small part of the area. Brodnica LP, along a section of 3 km, borders directly with Górzno-Lidzbark LP. Górzno-Lidzbark LP was created in 1990. The main attraction of the park is the varied terrain characterised by young glacial landforms: patches of moraine plateau, kames, drumlins, eskers, morainic hills, subglacial channels and kettle holes, and in the northern part of the Park, outwash plains. As in Brodnica LP, a large proportion of the Park is covered by forests (ca. 70%).

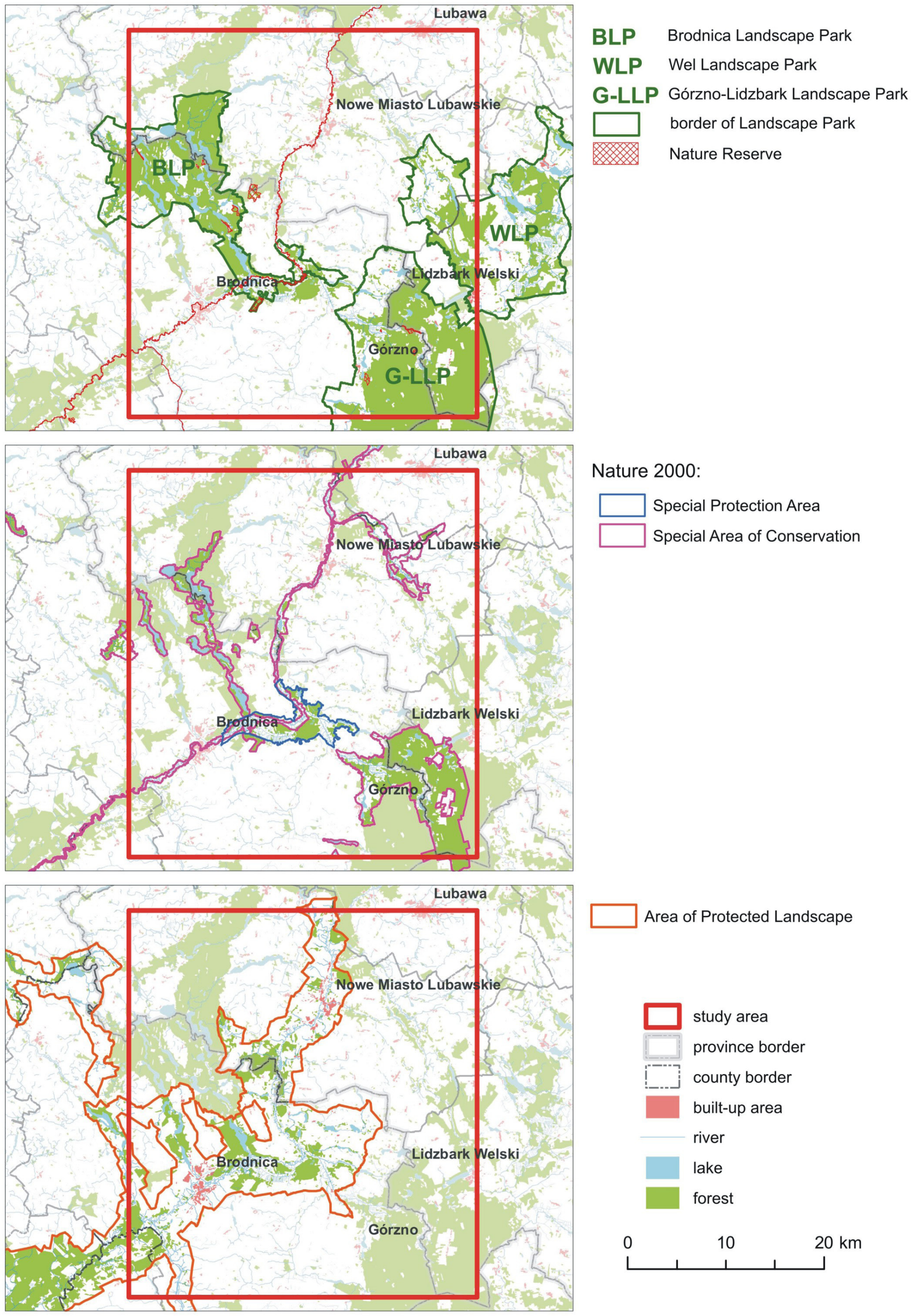

Fig. 3: Protected parts of the study area
Source: authors´ elaboration

The Drwęca Valley, crossing the central part of the study area, and adjacent parts of the direct catchment area are included in the Area of Protected Landscape of Drwęca Valley (Fig. 3). Along the river and in large parts of both LPs, a Special Area of Conservation (SAC) is located. A particularly valuable Natura 2000 site is a Special Protection Area (SPA): "Bagienna Dolina Drwęcy" (33.66 km^2), at the confluence of the Brynica and Drwęca rivers. In total, 67.7% of the study area is protected by law, mostly as landscape parks (28.5%).

4. Methods

To facilitate designation of the greenway in our study, the landscape was evaluated on the basis of visual landscape attractiveness (VLA). In the published literature on studies of visual attractiveness of landscape, some authors have emphasised that landscape attractiveness should not be treated a priori as incidental (Kostrowicki, 1992; Richling and Solon, 2011). That is why many researchers use questionnaire surveys and, on this basis, they build affective evaluations of the study areas (e.g. Cymerman et al., 1988; Pietrzak, 2006; Malinowska, 2010; Rogowski, 2012). When searching for an evaluation procedure, we referred to the one developed by Rutkowski (1978), which is consistent with the concept presented by Kostrowicki (1992), based on an analysis of about 300 evaluations from all over the world. This approach is preferred by many researchers (e.g. Warszyńska, 1970; Sołowiej, 1992; Śleszyński, 1999; Tucki, 2004; Myga-Piątek, 2007; Krukowska and Krukowski, 2009). In the case of such an evaluation, it is more difficult to defend the work against a claim of subjective evaluation than in the case of affective evaluation, but it must be remembered that the undertaken task and the very idea of VLA is supposed to identify the rules of judgments made by the participants (Armand, 1975). Moreover, it is impossible to make a completely objective evaluation, as perception in many cases depends on the psychological and physical factors of the evaluator, rather than on an independent assessment of the landscape itself (Wojciechowski, 1986). We strived to make a comprehensive and objective evaluation of the landscape using two categories: natural and cultural. For this purpose, suitable criteria needed to be developed, as described above.

The landscape evaluation was performed using a Vector Smart Map level 2 (VMap L2) on a scale of 1:50000 (using the available 2006 update package), in the EPSG 4326 system transformed to the EPSG 2180 system. We chose this map type because of the high precision and recent update of this military document, as compared to other maps (Bac-Bronowicz et al., 2007) available for the study area. Additionally, we updated the map to include objects affecting the visual attractiveness of landscape, on the basis of aerial photographs with the use of the Photogrammetry Station DEPHOS. In the analysis, we also used the database of historical buildings of the National Heritage Board of Poland.

The construction of databases, calculations, and final processing of the maps were performed with the use of the ESRI ArcGis 9.3 software. The created algorithms and the tools available in this application enabled us to obtain results relatively quickly and allowed for their elastic modelling. Raw data, after processing and addition to the evaluation database, could be freely included and excluded or transferred to a different category, or even the score could be changed. These apparently simple operations on the database enabled us to check various configurations of the developed evaluation procedure of cultural components of the landscape.

The evaluations were performed in elementary squares (artificial plots). The generated grid contained 5,609 elementary plots of 500 × 500 m, each covering a total of 0.25 km^2. The 4-fold decrease in square size, as compared with the standard 1 km^2 grid spacing, was due to the risk of excessive averaging of natural and cultural values and the resultant loss of some objective information about the study area (Chmielewski, 2012).

We evaluated separately the natural and cultural components of the landscape. In the evaluation of natural components of landscape, we used criteria suggested by Rutkowski (1978). Only the evaluation criteria of surface waters were modified (adapted because of the smaller size of squares) and water quality assessment was omitted (Tab. 1). The evaluation criteria for cultural components of the landscape were created from scratch. All of the objects were divided into two groups: those with increasing VLA scores and those with decreasing scores (Tab. 2).

In the evaluation procedure, we used the traditional classification of data collected in geographic information systems. The data were classified as points, lines or polygons, which increased the possibility of objective evaluation. For example, the object "permanent fencing/wall" running across the whole length of the square was treated as a line, while permanent fencing/wall of small length was treated as a point located in the square. We decided also to introduce some "replicates" of objects, i.e. objects of the same type, depending on dimensions, could be treated as a point, line, or polygon. This resulted primarily from data (VMap L2) used in the evaluation but also from the evaluation of natural components of the landscape. Rutkowski (1978) assumed that that the length of forest edge, lake shoreline or river determines landscape attractiveness. For this reason, linear data were extracted from areal data. The approach used here allowed us to maintain the clarity of the database and the inclusion of incomplete data, e.g. about the historical location of Teutonic castles. In Brodnica, the whole castle outline is

Criterion	Description	Score
Land relief	differences in altitude ≥ 25 m	5
	differences in altitude 21–25 m	4
	differences in altitude 16–20 m	3
	differences in altitude 11–15 m	2
	differences in altitude 5–10 m	1
	differences in altitude ≤ 5 m	0
Surface waters	water body, shoreline ≥ 125 m	4
	water body, shoreline ≤ 125 m	3
	watercourse or drainage ditches	2
	wetland/peatland	1
	no surface waters	0
Forests	forest edge ≥ 625 m long	5
	forest edge 500–625 m long	4
	forest edge 375–500 m long or forest covering > 80%	3
	forest edge 250–375 m long	2
	forest edge 125–250 m long	1
	forest edge ≤ 125 m long	0

Tab. 1: Evaluation criteria for the natural components of landscape
Source: Modified by the authors from Rutkowski's (1978) criteria

Type of object		Score									No. of objects	Area of objects [km^2]	Length of objects [km]
		Point object	Polygon object [% of elementary square area]				Line object [m]						
			0–25	26–50	51–75	76–100	0–62.5	62.6–125.0	125.1–187.5	187.6–250.0			
Increasing VLA	cemetery*	+ 1	+ 1	+ 2	+ 3	+ 4					25/39	0.423	
	roadside cross	+ 1									17		
	monument	+ 1									16		
	castle ruins*	+ 1	+ 1	+ 2	+ 3	+ 4					2/3	0.009	
	windmill	+ 1									1		
	historical building	+ 1									95		
	complex of historical buildings	+ 2									36		
Decreasing VLA	chimney	− 1									40		
	opencast mine	− 1	− 1	− 2	− 3	− 4					3/13	0.236	
	wind turbine	− 1									21		
	power pole	− 1									90		
	filling station/tank	− 1									78		
	distribution transformer	− 1	− 1	− 2	− 3	− 4					85/3	0.046	
	tower	− 1									5		
	radio tower	− 1									14		
	industrial plant	− 1	− 1	− 2	− 3	− 4					67/59	1.983	
	building	− 0.1									2,328		
	farm	− 0.1									6,771		
	spoil tip		− 1	− 2	− 3	− 4					7	0.222	
	warehouse or storage yard		− 1	− 2	− 3	− 4					15	0.503	
	built-up area		− 1	− 2	− 3	− 4					909	16.569	
	permanent fencing/wall						− 1	− 2	− 3	− 4	241		0.121
	power line						− 0.1	− 0.2	− 0.3	− 0.4	23		190.874
	temporary fencing						− 0.1	− 0.2	− 0.3	− 0.4	180		0.048

*Tab. 2: Evaluation criteria for visual landscape attractiveness (VLA) of the cultural components of landscape Note: *point and polygon objects*
Source: authors' original evaluation criteria

visible and in the map it can be presented as a polygon (and complete data can be obtained). Ruins of a Teutonic castle are also located in the village of Bratian (near Nowe Miasto Lubawskie). Unfortunately, in this case only small fragments of the walls are visible, so the object was treated as a point (incomplete data).

A literature search revealed two approaches to the treatment of polygons: one based on object area and the other based on border length. The opinion that borders in a landscape determine its attractiveness (Rutkowski, 1978; Śleszyński, 1999; Clay and Daniel, 2000; Krukowska and Krukowski, 2009, etc.) is reflected during the process of polygon evaluation in the calculation of the length of the evaluated object or calculation of its area relative to grid square size. During preparation of the evaluation procedure, we tested both the approaches in the course of the evaluation of wooded areas. We found no substantial differences between the results of elementary square evaluation based on object area and on border length. For this reason, we decided to apply the polygon evaluation method recommended by Rutkowski (1978) and, consequently, to make use of both approaches in the evaluation of the cultural components of the landscape.

The evaluation of hypsometric differentiation (Ar) of land relief should be based on differences in altitude, i.e. relative height. Individual squares were scored according to the applied scale (Tab. 1). The scale consists of 6 ranges of values (of 5 m each, except for the last one, which has no upper limit). During the evaluation, we took into account the maximum difference in altitude in the analysed elementary plot.

The second component of VLA evaluation, analysed in detail, were surface waters (Aw). In this category, elementary squares were scored for presence of running or standing waters (Tab. 1). Running waters include rivers and a network of drainage ditches, removing an excess of water from meadows and arable fields (2 points were added if a watercourse was present in the given elementary plot). Standing waters are primarily lakes (also oxbow lakes), so for their presence, 3 or 4 points were added, depending on the length of the shoreline in the given plot. The evaluation took into account also wetlands and peatlands (1 point was added if they were present in the plot) (Tab. 1). The coexistence of several components in one square resulted in summing up the scores, but we decided that their sum could not exceed 7. Thus for VLA scoring, the most favourable situation was coexistence of several objects in one elementary square.

Forests are valuable components of the landscape and, for this reason, they were treated as yet another component of landscape which needs to be evaluated. We classified as forest all types of wooded habitats, i.e. both mature forests and several-year-old forest plantations. We assumed that forest is most attractive in the places where it borders with other types of land cover (e.g. with meadows, a water body or arable fields). That is why an evaluation criterion was forest edge length (0–5 points) or its percentage contribution if forest accounted for over 80% (3 points, see Tab. 1). The scale consists of 6 ranges of values (of 125 m each, except for the last one, which has no upper limit).

When developing the evaluation criteria of cultural components of the landscape, we decided that the maximum score of this evaluation should only supplement the evaluation of natural components, because natural values more strongly determine the attractiveness of an area (Malinowska, 2010). In our opinion, other evaluation criteria for cultural objects (allowing higher scores than those resulting from the evaluation of natural components) should be applied if the study area includes objects of material culture of national or international importance. We assumed that cultural objects should be scored as follows (see Tab. 2):

- for points of low significance for VLA: ± 0.1;
- for lines of low significance for VLA: from ± 0.1 to ± 0.4;
- for points of high significance for VLA: ± 1;
- for polygons and lines of high significance for VLA: from ± 1 to ± 4; and
- for complexes of historical buildings: + 2.

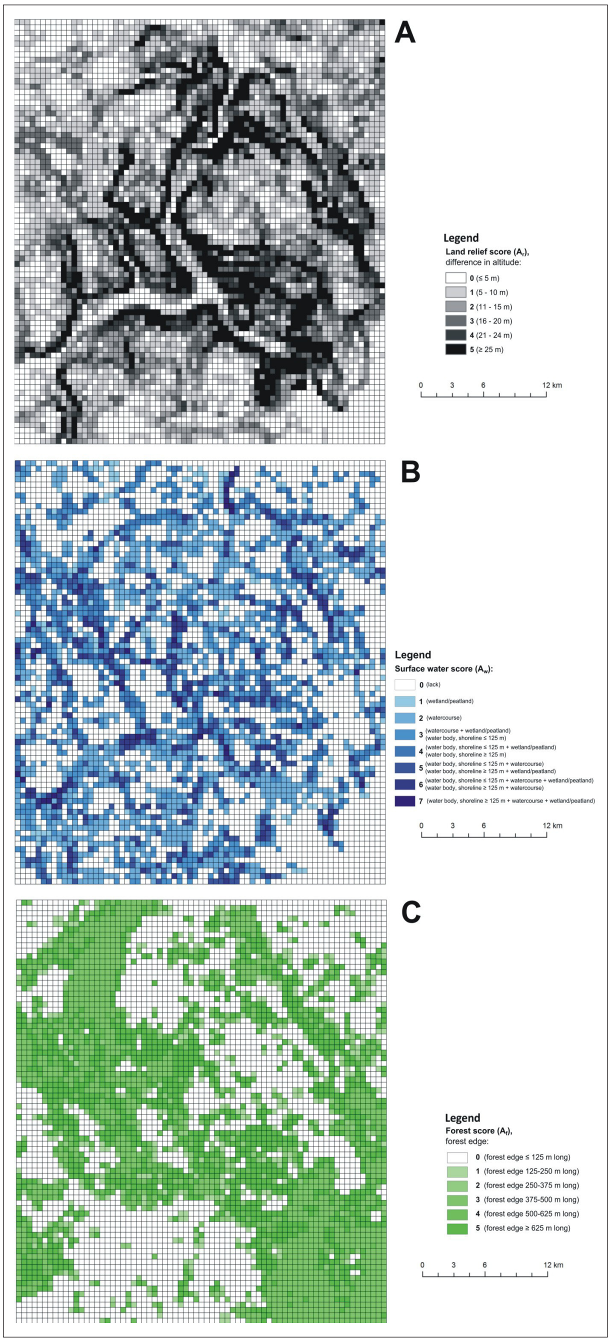

Fig. 4: Results of the evaluation of natural components of landscape (Legend: A – land relief (Ar); B – surface waters (Aw); and C – forests (Af))
Source: authors´ elaboration

The final VLA evaluation map should be constructed after taking into account the sum of the scores of natural components (AN, including land relief [Ar], forests [Af], and surface waters [Aw]) and cultural components (AC):

$$VLA = AN + AC \qquad [1]$$

where $AN = Ar + Af + Aw$, and $AC = AC^{+} + AC^{-}$.

5. Results

Results of the evaluation show that land relief significantly affects the attractiveness of the landscape (Fig. 4A). Visual attractiveness of landscape and its differentiation are in the study area determined by the location within various morphological units, sometimes with a distinct geological structure. The morphogenetic character of the study area, and primarily the fact that it is composed of the proglacial valley and the valley of the Drwęca, as well as areas of moraine plateau, strongly dissected by numerous subglacial channels, resulted in large differences in attitude. The distribution of elementary squares with the highest values of Ar is closely related to the outline of the moraine plateau edges, so that in the evaluation map of land relief, the distribution of morphological units of the study area can be read easily. Consequently, the areas classified as the most attractive were the slopes of the proglacial valley and the valley of the Drwęca: edges of the plateau as well as subglacial channels. In 1,444 plots (26%) of 0.25 km^2 each, the difference in altitude exceeded 20 m (Ar score: 4–5). The edges of the terraces are too narrow to give a readable effect in the evaluation process, very much like the lumps and bumps on the well-developed, extensive flood plain. VLA scores were the lowest for moraine plateaus and extensive basins in wider parts of the Drwęca valley (for 39% of all plots, the Ar scores were in the range 0–1).

The final picture of the evaluation of running or standing waters shows a mosaic pattern (Fig. 4B), but a high attractiveness of landscape is clearly related to the distribution of components of the hydrographic network, i.e. the Drwęca and lakes located in the subglacial channels. The Aw score was ≥ 4 points for 1,360 plots (24%). The least attractive parts of the study area (0–1 points) were the patches of the moraine plateau: 2,877 of elementary plots in total (51%).

Wooded habitats cover a large proportion of the study area. Attractive sites are located primarily in north-western and south-eastern parts of the study area (Fig. 4C), where the two landscape parks play the role of greenspaces. Special attention should be paid to the existing "chains" of forest patches, which link these two parts, and the relatively small contribution of small isolated or scattered forest patches. This is an important factor facilitating the designation of the greenway. The Af score was ≥ 3 points on 2,765 plots (49% of all plots), while 2,349 plots were devoid of forest (0 points, 42%).

The VLA evaluation map of the cultural components of landscape [AC] is a result of the evaluation of cultural objects increasing [AC^{+}] or decreasing [AC^{-}] visual attractiveness (Fig. 5). The components increasing the VLA value are usually scattered. Rarely, historical buildings are located very close to one another, but their positive effect on VLA is counterbalanced by their location in built-up areas (negative effect). AC^{+} was recorded on only 165 plots. In the study area, VLA values are more strongly affected by the components that have negative values (AC^{-}), which applies to 3,303 plots (59% of all elementary plots). On many plots (290), VLA values were so strongly reduced that they were finally negative. This indicates an overall negative human impact on the landscape. Plots of this type are located mostly in urban areas (towns and compact villages).

The analysis of spatial variation in VLA within the study area (Fig. 6), shows that the highest scores were recorded in woodlands with varied relief and water bodies or large watercourses (Fig. 7). They are found mainly in subglacial channels and the valley of the Drwęca. In contrast, the lowest VLA scores were recorded in moraine plateaus, mainly used for farming, with scattered or densely built-up areas (the latter greatly decreasing VLA; see Fig. 8).

The greenway was designed on the basis of a grid combining the road network with the results of VLA scoring (Fig. 6). The greenway uses only local asphalt roads running near visually attractive areas, taking into account the recommendations of the European Greenways Association. Next, field research was conducted to check the condition of the tourism infrastructure, available public transportation options, road surface quality and the distribution of food and beverage outlets.

6. Discussion and conclusions

The designated greenway satisfies our assumptions, i.e. it links the most naturally attractive sites protected within the landscape parks, which play the role of greenspaces. This is a recreational route both for tourists coming to Brodnica

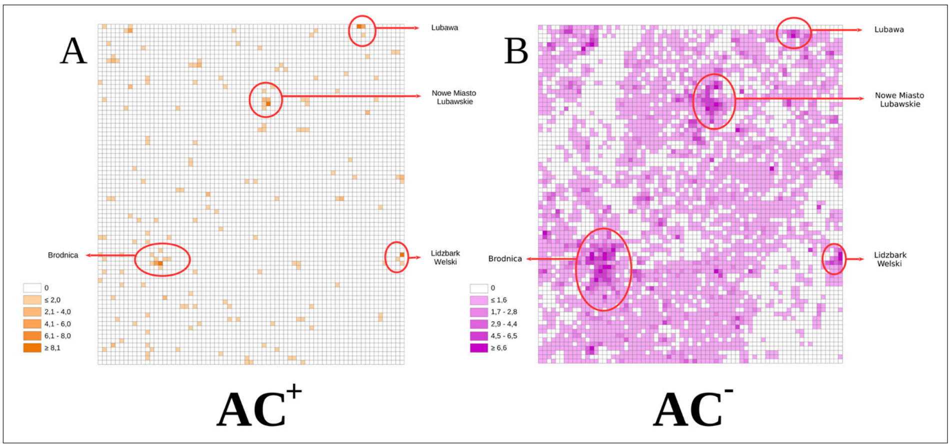

Fig. 5: Evaluation of cultural components of visual landscape attractiveness (VLA; Legend: A – objects increasing VLA (AC^{+}); B – objects decreasing VLA (AC^{-})). Source: authors´ elaboration

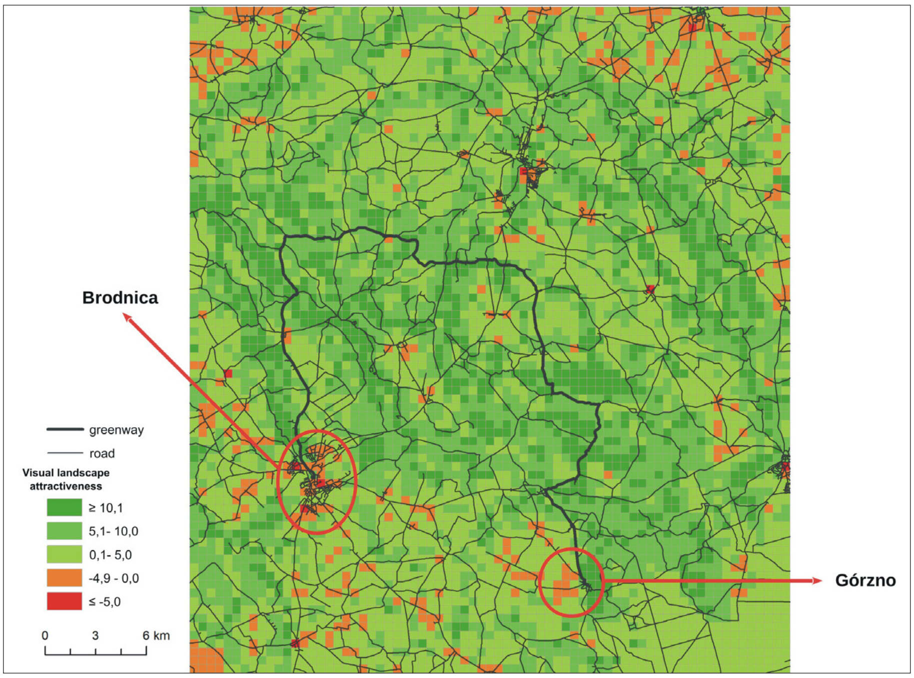

Fig. 6: Greenway designation between Brodnica and Górzno based on the current evaluation of visual landscape attractiveness (VLA) and the existing road network. Source: authors´ elaboration

Fig. 7: Example of a landscape with a high VLA value. Photo: Ł. Sarnowski

Fig. 8: Example of a landscape with a low VLA value. Photo: D. Brykała

Lakeland and for local inhabitants. It is used by cyclists, strollers, and horse riders, as two large stud farms are located near the greenway (in Głęboczek and Leźno). The varied relief and natural water bodies situated close to the greenway are parts of extensive landscape panoramas. The objects of cultural heritage, located close to the greenway, raise the attractiveness of the route. The scattered buildings of farms do not disturb the harmony of the rural landscape. Moreover, in the towns and villages on the route, visitors can see historical churches and cemeteries. Unfortunately, on the designated route there are no particularly interesting historical buildings or other objects that could be the destination for a tourist's travel.

The greenway, because of its predefined function, has the real possibility of encouraging the regional development of the study area, much greater than when a tourist trail is designed in a traditional way, where the space between selected objects (cultural or natural) is less important. The greenway is composed of existing local roads, allowing a more optimal utilization of natural and cultural resources of the landscape, primarily those located between the selected greenspaces. Because of these features, the idea of sustainable development can be implemented and the overlapping protected areas will not be subject to devitalization (Domon, 2011).

During the procedure of greenway designation, we found that it is advisable to make use of the Road Data Bank. The first edition of VMap L2 does not include complete and updated information about road conditions, which makes many analyses impossible, e.g. the least-cost path analysis or network analysis (Li et al., 2010; Tenga et al., 2011, Oh et al., 2007). It is possible to design one greenway on the basis of detailed field research, but when designating several greenways to link a larger number of greenspaces, it would be difficult to conduct extensive field research, so geographic information systems should be used.

In the procedure of greenway designation presented here, the use of the VLA evaluation proved to be very effective. The dense grid of elementary squares forced us to construct a clear and easily modified database. The database enabled us to make a graphic presentation of the introduced changes quickly, and consequently to specify the evaluation criteria more precisely. When developing the procedure, we took into account the possibilities of making the grid denser (by reducing the size of the elementary squares) or processing data concerning a larger area than in this study. The effectiveness of the algorithms was also confirmed for more complicated calculations and analyses, e.g. for the description of the range and field of view (Sarnowski, 2013; Sarnowski et al., 2013). We considered as relevant the inclusion of cultural components of landscape in the evaluation procedure, as well as the use of criteria distinguishing between categories of objects (points, polygons, and lines) and their various sizes.

One of the assumptions of this evaluation procedure was to strive for an objective assessment of the negative effect of cultural objects on VLA scores. During our research on VLA, the need for inclusion of cultural components of landscape was confirmed, but we assumed that they should not be treated exclusively as decreasing its attractiveness. Some components, particularly those regarded as objects of cultural heritage, increase the perceived value of landscape. Hence, a separate category of objects was distinguished. We observed that even single objects can significantly affect the evaluation results, but only when the evaluation is conducted in small-sized elementary squares. The results show that sites with a high AC^+ value are usually scattered and their aggregations are characteristic of only densely built-up areas with complexes of historical buildings. This approach is consistent with our assumptions that the evaluation of cultural components of the landscape should be considered as equally important as the evaluation of natural components. As a consequence, results of the evaluation of natural components of landscape should be corrected based on the evaluation of cultural components, i.e. increased or decreased. For 290 elementary squares, VLA scores were negative, i.e. a negative effect of human pressure prevailed in the perceptions of the given area. Aggregations of squares with negative VLA scores were found primarily in towns and densely built-up villages without objects of cultural heritage. We did not decide in this case to exclude them from the VLA analysis, assuming that they are an integral part of the greenway, and sometimes even of a greenspace.

It would be wrong to assume that built-up areas are always unattractive (Gobster et al., 2004). Our results confirm that densely built-up areas, despite their disputable visual landscape attractiveness, should be subject to an evaluation based on criteria formulated especially for urban areas (Wojciechowski, 1986; Cieślak, 2012).

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MORAVIAN GEOGRAPHICAL REPORTS

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Fig. 9: Agriculture field damaged by bank erosion. Several tens meters lateral shift of the Topľa River channel near the village Dubinné occured during winter 2010/2011 (Photo: Miloš Rusnák)

Fig. 10: The Topľa River channel abuts (length 580 m) against the Pleistocene (Würm) terrace (height 6 m) near the village Kurima (Photo: Miloš Rusnák)

Illustrations related to the paper by M. Rusnák et al.