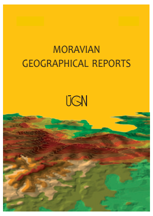

MORAVIAN GEOGRAPHICAL REPORTS

Institute of Geonics, The Czech Academy of Sciences

journal homepage: **http://www.geonika.cz/mgr.html**

doi: **10.1515/mgr-2016-0012**

DE GRUYTER OPEN

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*

Article history: *Received 16 December 2015; Accepted 10 June 2016; Published 30 September 2016*

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.

[a] Department of Geography, Faculty of Science, Masaryk University, Brno, Czech Republic (*corresponding author: J. Geletič, e-mail: *geletic.jan@gmail.com*)

[b] Department of Geography, Faculty of Science, Palacký University Olomouc, Olomouc, Czech Republic

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*

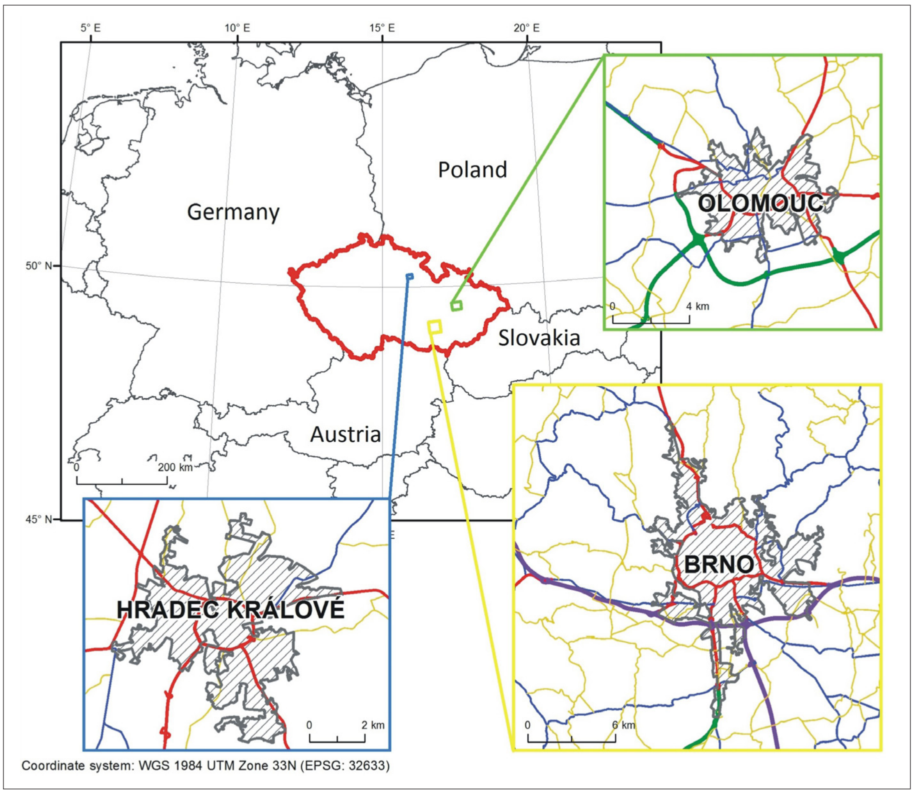

Fig. 1: The location of Brno, Hradec Králové, and Olomouc in Central Europe and the delineation of the experimental areas and compact urban development. Source: authors' elaboration (basic data: National geoportal INSPIRE)

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

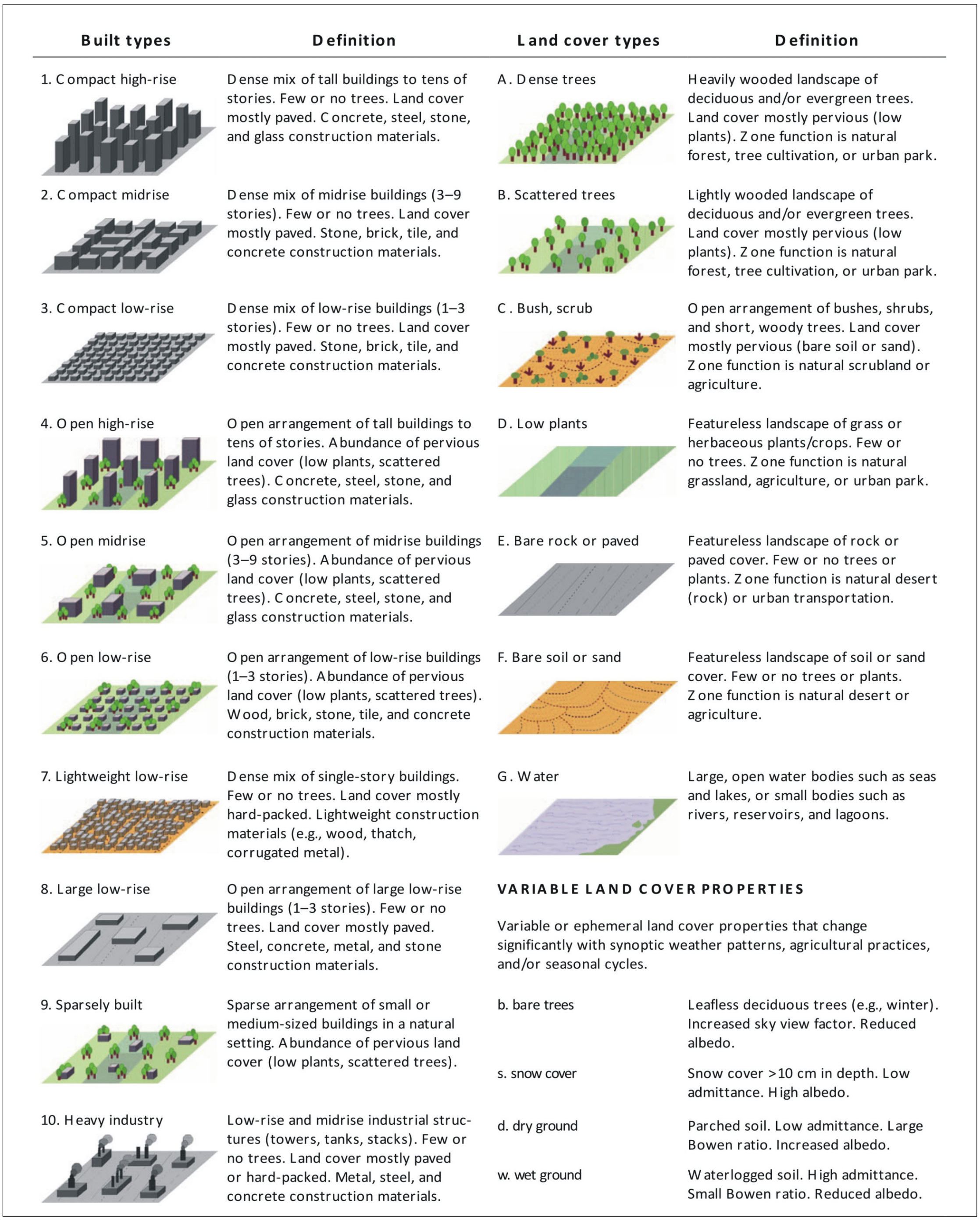

Fig. 2: Description of LCZ classes defined by Stewart and Oke (2012)
Source: Stewart and Oke (2012)

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}.

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

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}.

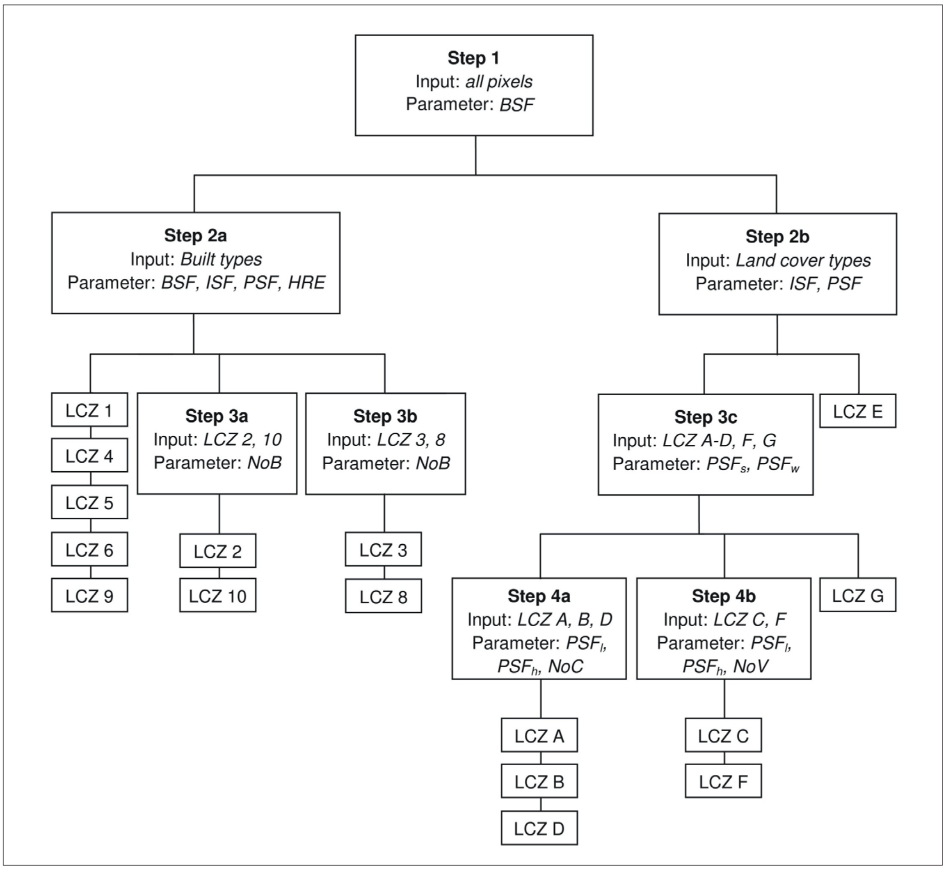

Fig. 4: The scheme of the proposed decision-making algorithm for classifying pixels into local climate zones (LCZ)
Source: authors' elaboration

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:

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

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:

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

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:

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

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:

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

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:

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

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:

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

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

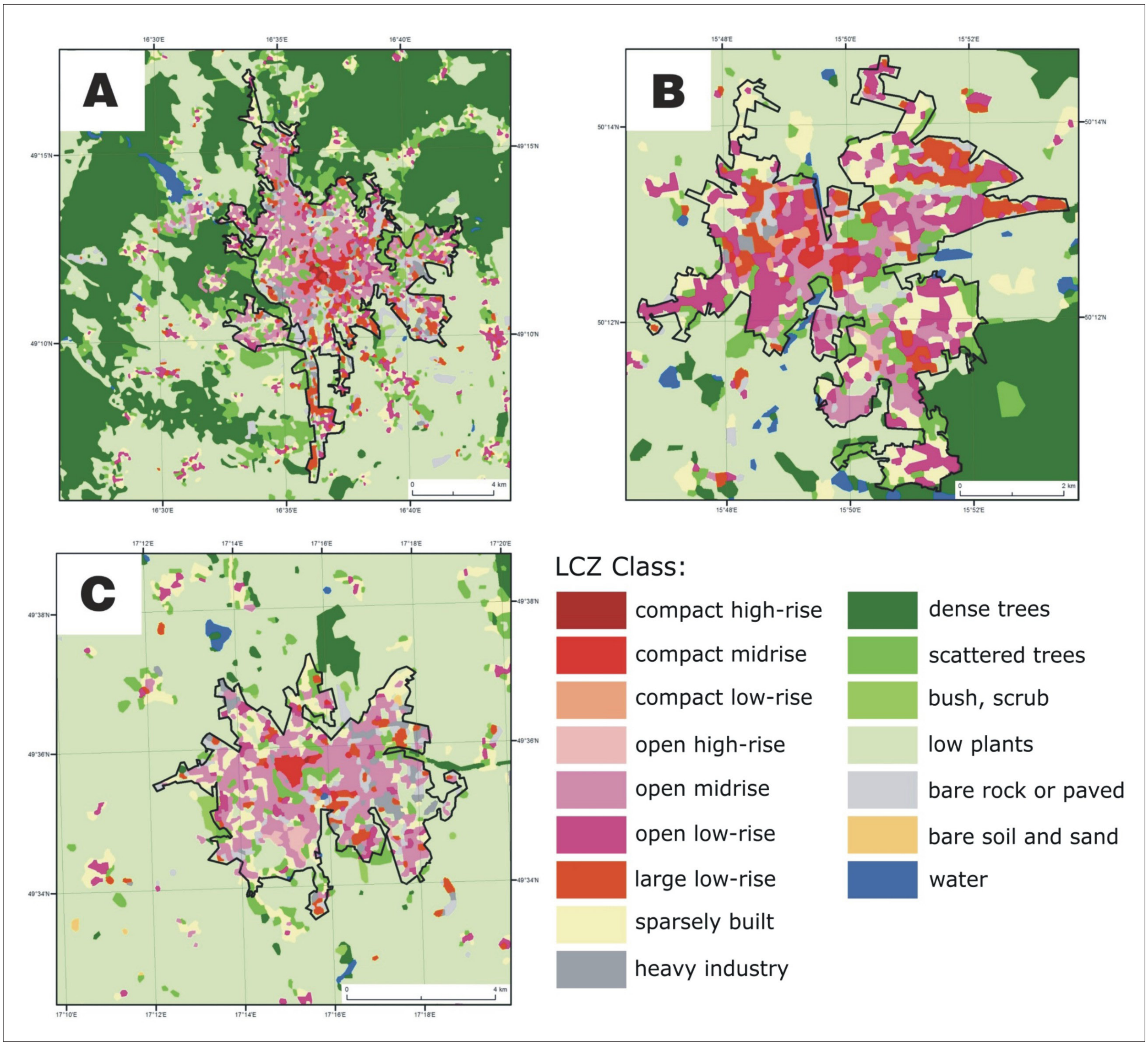

Fig. 5: Local climate zones in Brno (A), Hradec Králové (B), Olomouc (C) and its surroundings (Coordinate system: WGS 1984 UTM Zone 33N); black line represents compact city
Source: authors' elaboration

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

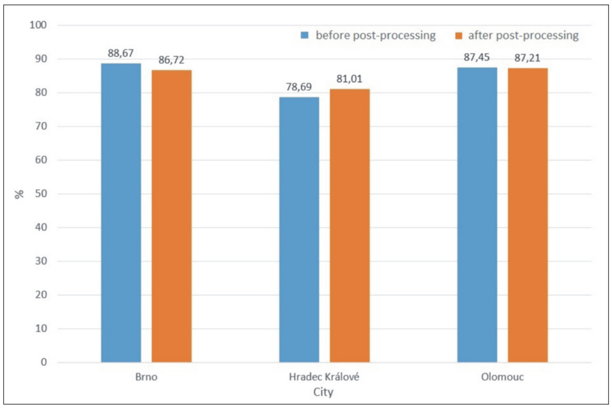

Fig. 6: Classification performance – percentage of pixels classified into LCZ classes in agreement with expert knowledge as overall producer accuracy before and after post-processing. Source: authors' elaboration

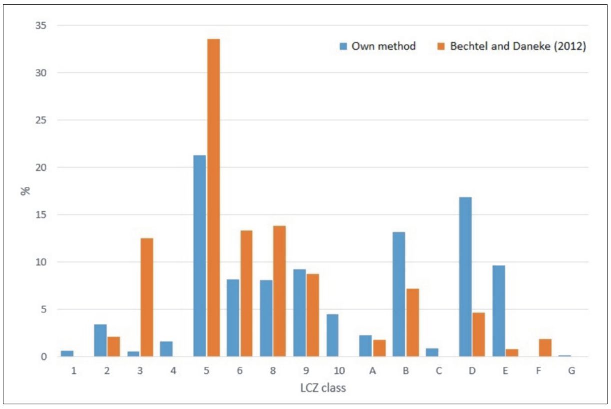

Fig. 7: Comparison of LCZ percentage in the compact development area of Brno with the methods presented here and with the method of Bechtel and Daneke (2012) Source: authors' elaboration

	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.

Acknowledgement

This study was funded from the project "Urban climate in Central European cities and global climate change", co-financed by the International Visegrad Fund as a standard grant (No. 21410222), in the years 2014-2015, which was carried out by the Global Change Research Centre, Academy of Sciences of the Czech Republic and Palacký University Olomouc. Jan Geletič was also supported by project MUNI/A/1315/2015.

References:

ALEXANDER, P. J., MILLS, G., FEALY, R. (2015): Using LCZ data to run an urban energy balance model. Urban Climate, 13: 14–37.

BECHTEL, B., DANEKE, C. (2012): Classification of local climate zones based on multiple earth observation data. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 5(4): 1191–1202.

BECHTEL, B., ALEXANDER, P. J., BÖHNER, J., CHING, J., CONRAD, O., FEDDEMA, J., MILLS, G., SEE, L., STEWART, I. (2015): Mapping local climate zones for a worldwide database of the form and function of cities. ISPRS International Journal of Geo-Information, 4(1):199–219.

BOKWA, A., HAJTO, M. J., WALAWENDER, J. P., SZYMANOWSKI, M. (2015): Influence of diversified relief on the urban heat island in the city of Kraków, Poland. Theoretical and Applied Climatology, 122(1–2): 365–382.

ČÚZK (2015): Český úřad zeměměřický a katastrální [cit. 17.10.2015]. Available at: http://www.cuzk.cz/

DOBROVOLNÝ, P. et al. (2012): Klima Brna. Víceúrovňová analýza městského klimatu. Brno, Masarykova univerzita.

EMMANUEL, R., KRÜGER, E. (2012): Urban heat island and its impact on climate change resilience in a shrinking city: The case of Glasgow, UK. Building and Environment, 53: 137–149.

FENNER, D., MEIER, F., SCHERER, D., POLZE, A. (2014): Spatial and temporal air temperature variability in Berlin, Germany, during the years 2001–2010. Urban Climate, 10: 308–331.

FRITZ, S., MCCALLUM, I., SCHILL, C., PERGER, C., SEE, L., SCHEPASCHENKO, D., VAN DER VELDE, M., KRAXNER, F., OBERSTEINER, M. (2012): Geo-Wiki: An on line platform for land cover validation and improvement of global land cover. Environmental Modelling and Software, 31: 110–123.

GÁL, T., BECHTEL, B., UNGER, J. (2015): Comparison of two different Local Climate Zone mapping methods. 9th International Conference on Urban Climate, Toulous. [cit 16-10-2015]. Available at: http://real.mtak.hu/28577/1/GD2-6-1551002_a.pdf

HALÁS, M., ROUBÍNEK, P., KLADIVO, P. (2012): Urbánní a suburbánní prostor Olomouce: teoretické přístupy, vymezení, typologie. Geographical Journal, 64(4): 289–310.

HOUET, T., PIGEON, G. (2011): Mapping urban climate zones and quantifying climate behaviors – An application on Toulouse urban area (France). Environmental pollution, 159(8): 2180–2192.

LECONTE, F., BOUYER, J., CLAVERIE, R., PÉTRISSANS, M. (2015): Estimation of spatial air temperature distribution at sub-mesoclimatic scale using the LCZ scheme and mobile measurements. 9th International Conference on Urban Climate, Toulous [cit. 16-10-2015]. Available at: https://www.researchgate.net/profile/Francois_Leconte2/publication/280317934_Estimation_of_spatial_air_temperature_distribution_at_submesoclimatic_scale_using_the_LCZ_scheme_and_mobile_measurements/links/55b25cb308ae9289a0854590.pdf

LEHNERT, M., GELETIČ, J., HUSÁK, J., VYSOUDIL, M. (2015): Urban field classification by "local climate zones" in a medium-sized Central European city: the case of Olomouc (Czech Republic). Theoretical and Applied Climatology, 122(3): 531–541.

LELOVICS, E., UNGER, J., GÁL, T., GÁL, V. (2014): Design of an urban monitoring network based on Local Climate Zone mapping and temperature pattern modelling. Climate Research, 60: 51–62.

LINDÉN, J., GRIMMOND, C. S. B., ESPER, J. (2015): Urban warming in villages. Advances in Science and Research, 12(1): 157–162.

MERBITZ, H., BUTTSTÄDT, M., MICHAEL, S., DOTT, W., SCHNEIDER, C. (2012): GIS-based identification of spatial variables enhancing heat and poor air quality in urban areas. Applied Geography, 33: 94–106.

OVER, M., SCHILLING, A., NEUBAUER, S., ZIPF, A. (2010): Generating web-based 3D City Models from OpenStreetMap: The current situation in Germany. Computers, Environment and Urban Systems, 34(6): 496–507.

PRZYBYLAK, R., USCKA-KOWALKOWSKA, J., ARAŹNY, A., KEJNA, M., KUNZ, M., MASZEWSKI, R. (2015): Spatial distribution of air temperature in Toruń (Central Poland) and its causes. Theoretical and Applied Climatology, 1–23.

SCHMID, H. P., CLEUGH, H. A., GRIMMOND, C. S. B., OKE, T. R. (1991): Spatial variability of energy fluxes in suburban terrain. Boundary Layer Meteorology, 54(3): 249–276.

SKARBIT, N., GAL, T., UNGER, J. (2015): Airborne surface temperature differences of the different Local Climate Zones in the urban area of a medium sized city. Urban Remote Sensing Event (JURSE), 2015 Joint, 1–4.

STEWART, I. D. (2011): A systematic review and scientific critique of methodology in modern urban heat island literature. International Journal of Meteorology, 31(2): 200–217.

STEWART, I. D., OKE, T. R. (2012): Local Climate Zones for Urban Temperature Studies. Bulletin of the American Meteorological Society, 93(12): 1879–1900.

STEWART, I. D., OKE, T. R., KRAYENHOFF, E. S. (2013): Evaluation of the 'local climate zone' scheme using temperature observations and model simulations. International Journal of Climatology, 34(4): 1062–1080.

STŘEDOVÁ, H., STŘEDA, T., LITSCHMANN, T. (2015): Smart tools of urban climate evaluation for smart spatial planning. Moravian Geographical reports 23(3): 47–56.

VYSOUDIL, M. et al. (2012): Podnebí Olomouce. Olomouc, Univerzita Palackého.

Please cite this article as:

GELETIČ, J., LEHNERT, M. (2016): GIS-based delineation of local climate zones: The case of medium-sized Central European cities. Moravian Geographical Reports, 24(3): 2–12. Doi: 10.1515/mgr-2016-0012.