Analysis of land cover changes using the Change Detection Toolbox: a case study of suburbanisation in the Senec district, Slovakia

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Abstract: *Land cover changes are currently being monitored very closely as they affect climate change, habitat disappearance and other related phenomena. One of the socio-economic processes manifested by significant land cover changes is suburbanisation. In terms of the land cover, suburbanisation is reflected in an increase of built-up areas in the hinterland of cities. In Slovakia, the process of suburbanisation is most pronounced in the hinterland of the capital Bratislava, with the most dynamic expansion of built-up areas in the district of Senec. We evaluated the land cover changes in the Senec district from 2000 to 2018 on the base of Urban Atlas data layers and satellite images. For these purposes, we designed a conversion table based on the Urban Atlas 2006 legend, which identifies nine types of changes within the urbanisation process. The conversion table allows effective visualization of landscape changes to assess their spatial distribution. Since the detection and evaluation of changes from multiple time horizons requires the repetition of several steps, we developed the Change Detection Toolbox (CDT) to automate this process. The toolbox consists of four tools that enable change detection, classification of change types, determination of hierarchical level of change and statistical evaluation of changes. Similar tools have not yet been available for the vector-based change detection. The toolbox was created using Python scripting language and it works in ArcGIS Desktop, the most widely used proprietary GIS software. The results produced by the CDT toolbox showed that in the years 2000-2018, almost 2000 ha of agricultural land were lost in favour of residential construction (especially in the municipality of Chorvátsky Grob), construction of logistics parks and the Bratislava motorway bypass. However, in the last evaluated period 2012-2018, there was a slight slowdown in the intensity of residential construction, which may be related to persistent problems with transport to and from the capital during the morning and afternoon peak hours.*

Keywords: *suburbanisation, land cover, change detection, toolbox, ArcGIS*

Introduction

Changes in land use and land cover are currently among the phenomena that have the greatest impact on the state of the environment in Slovakia and worldwide. Extensive deforestation and soil sealing prevent soil retention and contribute to a drier and warmer climate. The structure of the agricultural landscape changes in connection with the setting of agricultural subsidies as well as other market characteristics, which in Slovakia causes the abandonment of the traditional agricultural landscape (Lieskovský et al. 2015). Furthermore, the suburbanisation takes place in the proximity of larger towns, which is related, with expansion of built-up areas at the expense of agricultural land. These changes are reflected in the land cover (LC) as the uppermost layer of the landscape sphere. LC represents the materialized reflection of the natural spatial assets and simultaneously that of the present land use by society or by man created or cultivated objects of landscape (Feranec and Oťahel, 2001). Globally, the remote sensing data, which capture the state of LC at a certain point in time, is the most widely used source for investigating the land changes.

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In Europe, the CORINE Land Cover (CLC) and the Urban Atlas (UA) projects use high-resolution satellite data to interpret land use/land cover classes and to monitor their changes. Based on the CLC and UA data, several case studies have been developed to address land cover changes in specific areas of Europe and Slovakia. Trends in European landscape changes between 1990 and 2000 were reviewed by Feranec et al. (2010) based on the CLC data. Changes in the land cover of Slovakia between 1990 and 2012 based on the CLC data were evaluated in a comprehensive study by Feranec et al. (2018). Pazúr and Bolliger (2017) examined various factors affecting land changes in Slovakia between 1980 and 2012, identified from the CLC data. Druga, Falťan and Herichová (2015) modified the CLC legend for mapping of land cover in Slovakia in scale 1:10 000, their proposal was further refined and extended by Oťahel et al. (2017).

One of the socio-economic processes, which is manifested by significant changes in land cover, is suburbanization. We can define it as a process of expansion of suburban territories under the influence of intensive daily relations with the core city (Šveda and Šuška 2019). In terms of the land cover, suburbanisation is reflected in an increase in built-up areas, whether residential or industrial, transport and service (Oťahel et al. 2020). A common side effect of suburbanisation is the so-called urban sprawl, i.e. the expansion of low-density land use forms on undeveloped land around a city driven by a multitude of processes (Kovács et al. 2019). Although this concept is mainly associated with the large settlements around North American cities, urban areas throughout Europe have also expanded more rapidly than the growth of population during the post-war decades, and there is no apparent slowing down in these trends (EEA 2006). Also the cities in Central and Eastern Europe, previously compact as a result of socialist planning, are now facing the same threats of rapid urban sprawl (e.g., Pazúr et al. 2017, Kovács et al. 2019, Cieslak et al. 2020). In Slovakia, built-up areas are increasing mainly at the expense of arable land (Kopecká et al. 2015). The process of suburbanisation is most pronounced in the hinterland of the capital Bratislava (Šveda 2011, 2019), with the most dynamic expansion of built-up areas in the district of Senec (Pazúr et al. 2015).

Šveda (2011) was the first to identify suburbanisation processes in the years 1990 to 2006 in the hinterland of Bratislava using the CLC data. Pazúr et al. (2019) extended this analysis to the wider period from 1980 to 2018. Oťahel et al. (2020) examined the suburbanisation processes in the hinterland of Prešov in eastern Slovakia also based on the CLC data. The dynamics of built-up areas in Slovakia and in more detail in the Bratislava region were evaluated using the CLC and the UA data by Kopecká et al. (2015) and Pazúr et al. (2015). Pazúr et al. (2017) investigated changes in the urbanised landscape in Prague and Bratislava between 2006 and 2012 using the UA data. Agricultural land changes are also identifiable based on the Land Parcel Identification System (LPIS). In the hinterland of Bratislava, Kopecká, Szatmári and Sviček (2019) evaluated changes in the agricultural landscape in this way.

Suburbanisation, as well as other land cover changes, are the most often examined using the remote sensing data. The aerial photographs have been used to map land changes since the 1950s, while the Landsat satellite image archive continuously capturing the LC state since the 1970s. To go further into the past, we need to use old maps such as the military survey maps (Moravčík and Benová 2020). Currently, the satellite imagery collections are also available through the Google Earth Engine (Gorelick et al. 2017), which allows automated mapping of LC changes over a wide time and space range (e.g., Huang et al. 2017).

Change detection is the process of identifying differences in the state of an object or phenomenon by observing it at different times (Singh 1989). In general, change detection techniques can be grouped into two types (Lu et al. 2004): (1) those detecting binary change/nonchange information, and (2) those detecting detailed “from-to” change. The first group includes techniques of image algebra and transformations, while the second group comprises the classification category (pixel-based and object-based), advanced models, GIS approach and visual analysis. Visual analysis, namely the backdating and the updating, is also used in the CLC and the UA operational programs.

The evaluation of the detected changes most often consists of comparing the area of LC classes in different periods and calculating the gains and losses or net changes of individual classes. For analysing of change processes, it is also important to identify the transitions from one LC class to another or the contributors to a class change. Filtering changes based on their size allows us to identify the main types of transitions. Subsequently, the transitions are often grouped into types based on the driving forces or the characteristic states of the landscape after the changes have been made (Cebecauerová and Cebecauer 2005). The need for automation of the above-mentioned tasks increases with the number of time slices used.

The change detection process usually takes place in geographical information systems (GIS), with input LC data in vector or raster form. Automatic raster-based change detection is provided by the Land Change Modeler (LCM), a part of the TerrSet software (formerly Idrisi). LCM works also as an extension for ArcGIS and allows us predicting changes for the future using the artificial neural networks (Stanková and Šošovičková 2013). For automated detection and evaluation of LC changes based on the vector data, a tool like LCM is not yet available. However, the local and regional case studies most often work with a vector format that eliminates the information loss due to the limited resolution. For these reasons, we developed a Change Detection Toolbox (CDT) for vector data processing in ArcGIS, the most widely used proprietary GIS software. The proposed toolbox provides four tools to create a change layer and contingency table, classify changes into various types and hierarchical levels, as well as statistically evaluate changes at the class level.

Several specialized toolboxes have been developed in ArcGIS over the past decade, such as the ArcGeomorphometry toolbox for extracting geomorphometric land surface variables and features from digital elevation models (Rigol-Sanchez, Stuart and Pulido-Bosch 2015), FluvialCorridor toolbox for multiscale research of river corridors (Roux et al. 2015), Sound Mapping Tools to model anthropogenic noise propagation (Keyel et al. 2017), Line of Sight Analyst for visibility analyses (Caha 2018), or a novel toolbox to estimate water crop demands using multi-source satellite imagery (Ramírez-Cuesta et al. 2018).

The aim of this paper was to analyse the development of suburbanisation in the district of Senec using the CDT toolbox. We evaluated suburbanisation based on the LC changes in three periods, using the UA 2006 and 2012 data layers along with the backdated and updated layers for the years 2000 and 2018. To evaluate the LC changes, we proposed a conversion table in terms of the works of Pazúr and Bolliger (2017) and Oťahel et al. (2020), including nine types of changes in artificial surfaces.

Study area and data

The studied area of the Senec district is often considered the most dynamically developing region in Slovakia in terms of land cover changes or population growth. The district is located in the south-western part of Slovakia in the immediate vicinity of the capital Bratislava (fig. 1). The entire territory of the district with an area of 360 km^2 lies on the Podunajská nížina plain (Danubian Lowland). The district consists of 28 municipalities and one town (Senec), and as of 31 December 2018, the district had more than 88 000 inhabitants (ŠÚSR 2019). The D1 motorway crosses the northern part of the district, the R7 expressway passes through the southern part and the Bratislava D4/R7 bypass is currently under construction. The main railway line of the Pan-European Corridor IV passes through the town of Senec and other municipalities, and the regional line Bratislava-Komárno runs through the southern part of the district. Such transport infrastructure attracts residents of the capital to move to rural municipalities at a reasonable distance for daily commuting.

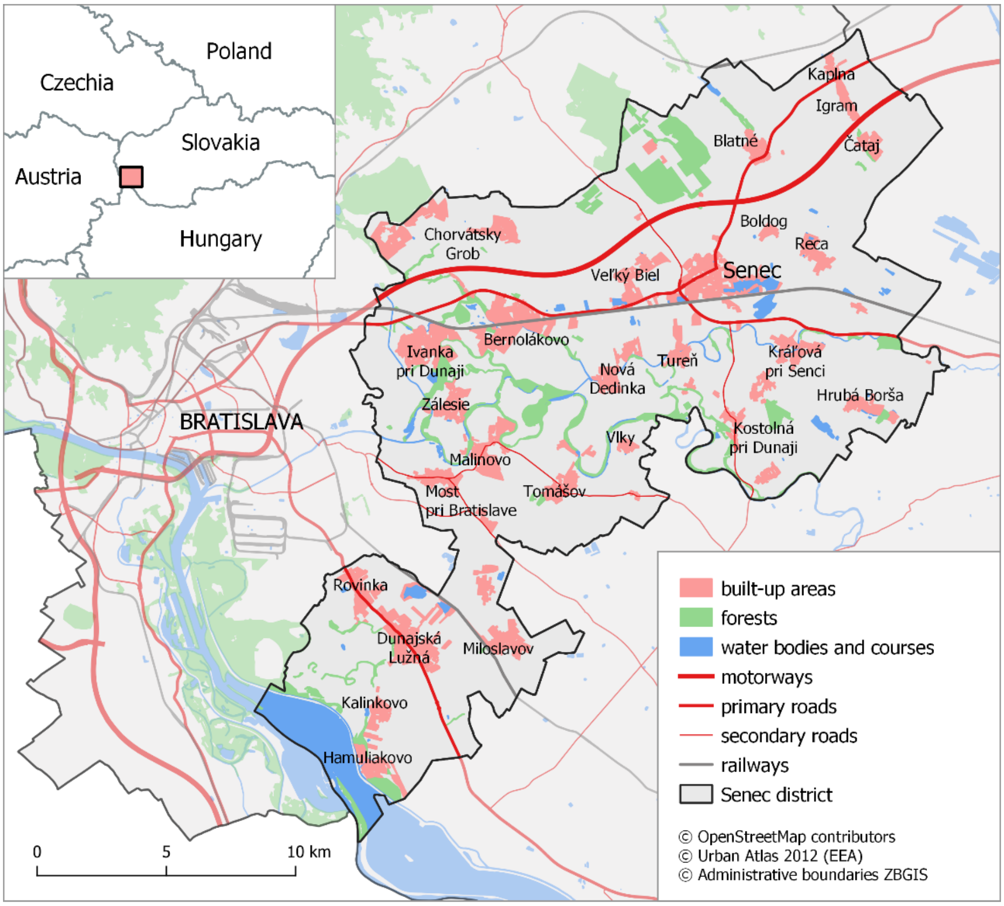

Fig. 1. *Location of the study area*

The LC changes in the Senec district were identified using the UA 2006 and 2012 data layers. In addition, LC layers from 2000 and 2018 were created by the backdating and updating of original UA layers on the base of satellite images. The UA data are generated within the Copernicus Programme in order to collect and provide reliable, inter-comparable, high-resolution land use and land cover data for the European Functional Urban Areas. The UA 2006 nomenclature (tab. 1) consists of 17 classes of artificial surfaces with the minimum mapping unit (MMU) of 0.25 ha and three other classes with the MMU of 1 ha (EC 2011). For the UA 2012 layer, the nomenclature was extended from three up to ten non-artificial classes (EC 2016). In order to detect LC changes, we applied the 2006 nomenclature to all time horizons.

For the visual interpretation of the LC state in 2000, we used Landsat 5 and Aster satellite images, while the LC state in 2018 was interpreted based on Sentinel-2 images. In addition, the UA 2006 and 2012 layers were confronted with the Landsat 7 satellite images to reveal possible errors. An overview of the satellite images used in the process of visual interpretation is provided in tab. 2.

Tab. 1. *Urban Atlas 2006 nomenclature*

Code	Nomenclature
1	Artificial Surfaces
1.1	Urban Fabric
11100	Continuous Urban Fabric (soil sealing > 80%)
11210	Discontinuous Dense Urban Fabric (soil sealing 50-80%)
11220	Discontinuous Medium Density Urban Fabric (soil sealing 30-50%)
11230	Discontinuous Low Density Urban Fabric (soil sealing 10-30%)
11240	Discontinuous Very Low Density Urban Fabric (soil sealing < 10%)
11300	Isolated structures
1.2	Industrial, commercial, public, military, private and transport units
12100	Industrial, commercial, public, military and private units
12210	Fast transit roads and associated land
12220	Other roads and associated land
12300	Railways and associated land
12400	Port areas
1.3	Mine, dump and construction sites
13100	Mineral extraction and dump sites
13300	Construction sites
13400	Land without current use
1.4	Artificial non-agricultural vegetated areas
14100	Green urban areas
14200	Sports and leisure facilities
2 (20000)	Agricultural areas, semi-natural areas and wetlands
3 (30000)	Forests
5 (50000)	Water

Source: EC (2011)

Tab. 2. *Satellite images used for the visual interpretation*

Data layer	Satellite image	
	Satellite	Date
UA 2000	Landsat 5	18.8.2000
	Aster	2.10.2002
UA 2006	Landsat 7	6.10.2006
UA 2012	Landsat 7	6.10.2012
UA 2018	Sentinel-2	30.10.2018

Methods

Visual interpretation

In the visual interpretation, we worked only with the classes of artificial surfaces, while creating new or editing existing areas of these classes (Šolc 2018). The principle of backdating and updating is that only the changed land cover polygons are modified, while the unchanged polygons remain untouched. Such workflow eliminates the problem of residual polygons when overlapping the data layers from two time horizons (Feranec et al. 2007).

A report from the verification of UA 2012 data prepared by Szatmári et al. (2019) states that the continuous urban fabric class acquired a user accuracy of only 10%. Discontinuous urban fabric classes with different degree of soil sealing were also often confused. In the territory of the Senec district, the most frequent errors include the misalignment of roads narrower than the minimum width of 10 m in residential parts of municipalities. As these errors were very numerous and did not have much impact on the results of change detection, we left them uncorrected.

Proposal of the conversion table

Based on the UA 2006 legend, the conversion table was designed for all potential combinations of changes (tab. 3). The conversion table comes from the standard conversion table for the second hierarchical level of CLC, which consists of seven basic types of changes (Pazúr and Bolliger 2017). For the UA 2006 legend, four of them are applicable, i.e. urbanisation, afforestation, deforestation and other changes. The main purpose in designing the conversion table was to describe in more detail the individual sub processes involved in the urbanisation process. The urbanisation based on the CLC legend has already been divided by Oťahel et al. (2020) to the urbanisation by residential built-up areas and urbanisation by industrial, transport and service built-up areas. Based on the UA legend, we could also recognize the densification of buildings, urbanisation with artificial, non-agricultural vegetated areas, urbanisation with construction sites or completion of the started construction of various types of built-up areas. In total, we have identified nine types of changes, described as follows:

Tab. 3. *Conversion table of LC changes for the UA 2006 legend*

	11100	11210	11220	11230	11240	11300	12xxx	13100	13300	13400	14100	14200	20000	30000	50000
11100	0	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	7	7	7
11210	1.1	0	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	7	7	7
11220	1.1	1.1	0	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	7	7	7
11230	1.1	1.1	1.1	0	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	7	7	7
11240	1.1	1.1	1.1	1.1	0	1.9	1.9	1.9	1.9	1.9	1.9	1.9	7	7	7
11300	1.1	1.1	1.1	1.1	1.1	0	1.9	1.9	1.9	1.9	1.9	1.9	7	7	7
12xxx	1.9	1.9	1.9	1.9	1.9	1.9	0	1.9	1.9	1.9	1.9	1.9	7	7	7
13100	1.9	1.9	1.9	1.9	1.9	1.9	1.9	0	1.9	1.9	1.9	1.9	7	7	7
13300	1.5	1.5	1.5	1.5	1.5	1.5	1.6	1.9	0	1.9	1.7	1.7	7	7	7
13400	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	0	1.9	1.9	7	7	7
14100	1.1	1.1	1.1	1.9	1.9	1.9	1.1	1.9	1.1	1.9	0	1.9	7	7	7
14200	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	0	7	7	7
20000	1.2	1.2	1.2	1.2	1.2	1.2	1.3	1.9	1.8	1.9	1.4	1.4	0	4	7
30000	1.2	1.2	1.2	1.2	1.2	1.2	1.3	1.9	1.8	1.9	1.4	1.4	5	0	5
50000	1.2	1.2	1.2	1.2	1.2	1.2	1.3	1.9	1.8	1.9	1.4	1.4	7	4	0

1.1 densification of existing urban fabric
1.2 urbanisation by residential built-up areas
1.3 urbanisation by non-residential built-up areas
1.4 urbanisation by artificial vegetated areas
1.5 completion of residential construction
1.6 completion of non-residential construction
1.7 completion of construction of artificial vegetated areas
1.8 urbanisation by areas under construction
1.9 other changes of artificial surfaces

0 no change
4 afforestation
5 deforestation
7 other changes

Notes: LC classes are listed in table1
Label 12xxx includes 6 classes: 12100, 12210, 12220, 12230, 12300, 12400

Source: Based on the CLC conversion tables introduced in Pazúr and Bolliger (2017) and Oťahel et al. (2020)

1.1 Densification of existing urban fabric

This category includes changes representing the soil sealing process within an existing residential development. These are transitions between the urban fabric classes (11100, 11210, 11220, 11230, 11240 and 11300), always going in the direction from a class with a lower proportion of impervious surface to a class with a higher proportion of impervious surface. We also include in this category changes from green urban areas (14100) to the urban fabric with medium to high density (classes 11100, 11210, 11220), to industrial, commercial, public, military, private and transport units (classes 12xxx) or to construction sites (13300). Densification of urban fabric can be observed in almost all cities today. Residents often reacts negatively to this trend, especially when it is associated with the occupation of publicly available green spaces. Densification often takes place by converting areas without typical use (class 13400) into built-up areas, but this class includes also former industrial areas (brown fields), so we cannot clearly mark this transition as densification.

1.2 Urbanisation by residential built-up areas

This category includes all changes from the agricultural areas, semi-natural areas, forests and water (classes 20000, 30000 and 50000) to the urban fabric (classes 11xxx).

1.3 Urbanisation by non-residential built-up areas

This category includes all changes from the agricultural areas, semi-natural areas, forests and water (classes 20000, 30000 and 50000) to the industrial, commercial, public, military, private or transport units (classes 12xxx).

1.4 Urbanisation by artificial vegetated areas

This category includes changes from the agricultural areas, semi-natural areas, forests and water (classes 20000, 30000 and 50000) to the green urban areas and sports and leisure facilities (classes 14100 and 14200).

1.5 Completion of residential construction

This category includes changes from the construction sites (class 13300) to the urban fabric (classes 11xxx).

1.6 Completion of non-residential construction

This category includes changes from the construction sites (class 13300) to the industrial, commercial, public, military, private or transport units (classes 12xxx).

1.7 Completion of construction of artificial vegetated areas

This category includes changes from the construction sites (class 13300) to the green urban areas and sports and leisure facilities (classes 14100 and 14200).

1.8 Urbanisation by areas under construction

This category includes all changes from agricultural areas, semi-natural areas, forests and water (classes 20000, 30000 and 50000) to the construction sites (class 13300).

1.9 Other changes of artificial surfaces

This category includes all other changes of artificial surfaces that could not be included in any of the previous categories. Most often, there were various changes from and to the class of land without current use (class 13400), but we also recorded the formation of mineral extraction and dumpsites (class 13100), construction of green urban areas (class 14100) in places with an originally different function, or construction of sports and leisure facilities (class 14200).

The above list includes the main effects of the urbanisation process on the LC state, i.e. densification of built-up areas, occupation of agricultural land, forests and semi-natural areas by construction and built-up areas with different functions, completion of construction. We used the proposed conversion table to classify the changes identified in the Senec district in the evaluated periods.

Detection and evaluation of changes using the CDT toolbox

Detection and evaluation of vector-based LC changes in common GIS programs requires several steps, specifically the analytical overlapping of two vector layers, adding the change code to the attribute table of resulting change layer and converting the areas of individual transitions into a contingency table. From this table other characteristics such as gains, losses, net changes etc. need to be derived in the table editor environment. Optionally, the graphs of these characteristics can also be created.

The CDT toolbox automates the change detection workflow within ArcGIS, the most widely used commercial GIS system. It enables the detection of changes, their classification into types, classification by hierarchical levels and statistical evaluation of changes. The toolbox was created using the Python scripting language version 2.7.3. It is designed for ArcGIS 10.6, but it is also available for older versions, which include the matplotlib and xlwt libraries (Žubrietovský 2016). It is currently distributed under the GNU General Public License Version 3 and can be downloaded at https://gis.fns.uniba.sk/projekty/CDT/index_en.htm. A typical workflow of using the CDT toolbox is shown in fig. 2.

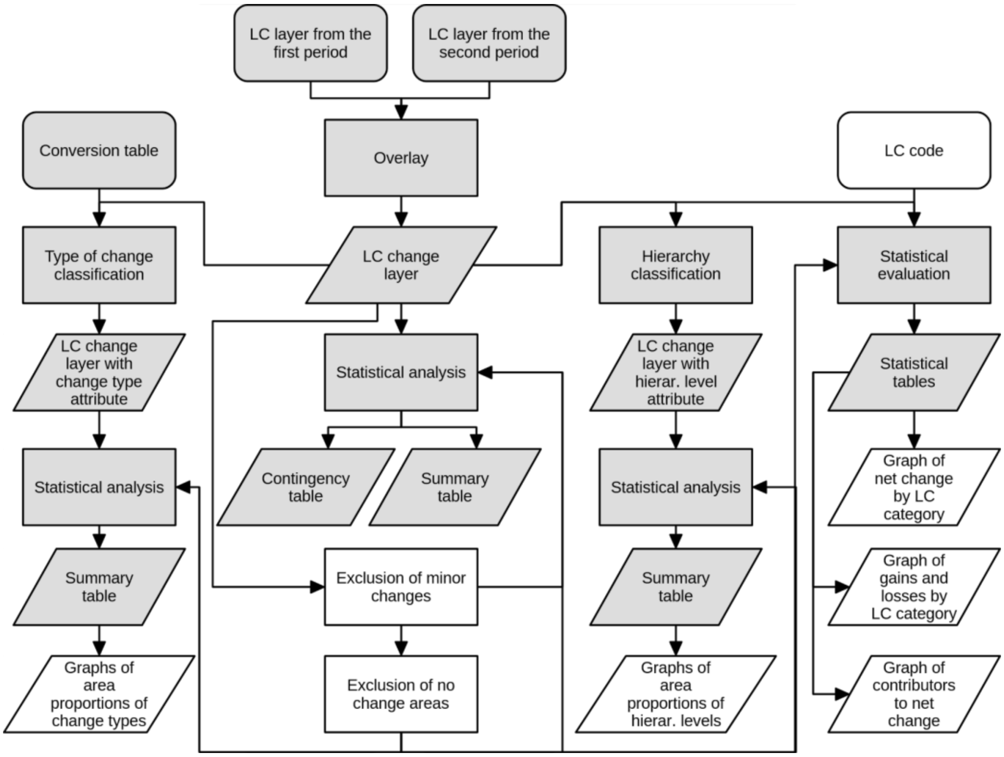

Fig. 2. *A typical workflow of using the Change Detection toolbox*

The CDT toolbox consists of four tools:

1. Detection of changes
2. Classification of changes
3. Hierarchy of changes
4. Statistical evaluation of changes

Detection of changes

The first tool analytically compares input vector layers from two periods and creates a new change layer and contingency table in xls format. The new attributes of change code and change area are written to the change layer attribute table. The change code is written as a combination of the selected LC codes from the first and the second layer, separated by an underscore. With the change area attribute, it is possible to select a unit of area, the user has the choice of acres, hectares, square meters and square kilometres.

Summary table as the optional output provides information on the area and frequency of each LC combination. The user can use this table as the basis for creating the conversion table needed to classify changes into types. A type code can be written to the new column for each LC combination.

Two optional parameters help us identify the main types of changes. The first one allows to exclude areas that have not changed in the period under review. The second parameter allows us to exclude areas smaller than the specified threshold. The possibility of excluding unchanged areas is also available in the other three tools as these areas influence the resulting statistics (e.g., when calculating relative proportions).

Classification of changes

The second tool sorts the changes based on the user-provided conversion table. This tool does not create a new change layer, it only updates an existing change layer by adding a change type attribute. It also creates a summary table of absolute and relative proportions of each type of change in the total area and graphs based on these values.

Hierarchy of changes

The third tool determines the hierarchical level at which the change occurred. It assumes the use of a hierarchical legend such as the CLC legend in the input LC layers. Like the previous tool, it does not create a new change layer, only adds an attribute containing a hierarchical level to the existing change layer. The tool also creates a summary table of the proportions of the individual hierarchical levels in the total area and graphs based on these values.

Statistical evaluation of changes

The last tool creates the three types of statistics tables based on the input change layer. The first table quantifies the net change of the individual LC classes. The second table summarizes the gains and losses of the individual LC classes. Optionally we can also create graphs from these tables. The third type of statistical calculation is optional. It is performed when the user enters a class code for which he wants to identify contributors to the net change. The result is a table and a graph.

Results and discussion

Quantitative evaluation of the LC changes

The LC changes in three evaluated periods are documented by the graphs of absolute proportions of change types in the total area of changes created by the Classification of changes tool (fig. 3). In the years 2000-2006, urbanisation with residential built-up areas prevailed, but there were also the construction of industrial areas (logistics park Senec) and the beginning of new residential construction projects in the municipality of Chorvátsky Grob and also in other municipalities. In the years 2006-2012, the construction started in the previous period was completed (type of change 1.5) and at the same time, other construction projects have started on three times the area of the previous period (type of change 1.8). The largest area was occupied by other new residential projects in the municipality of Chorvátsky Grob and the beginning of the construction of a golf course and adjacent residential area in the municipality of Hrubá Borša. In addition, other areas of agricultural land were taken directly by residential and industrial development (type of change 1.2 and 1.3).

The most extensive changes took place in the last evaluated period 2012-2018, when, in addition to the completion of projects under construction, residential construction on an area of more than 300 ha began and finished, e.g., in the municipalities of Malinovo, Most pri Bratislave, Rovinka or Dunajská Lužná. In the same period, new construction began with the similar area of more than 300 ha, but these changes were mainly related to the start of construction of the Bratislava D4/R7 bypass. The construction of new residential projects slightly decreased in comparison with the previous periods. During the years 2000-2018, the existing housing estates were also densified (e.g., in the municipalities of Bernolákovo, Ivanka pri Dunaji, Dunajská Lužná, Senec) and the Senec logistics park was expanded by additional areas.

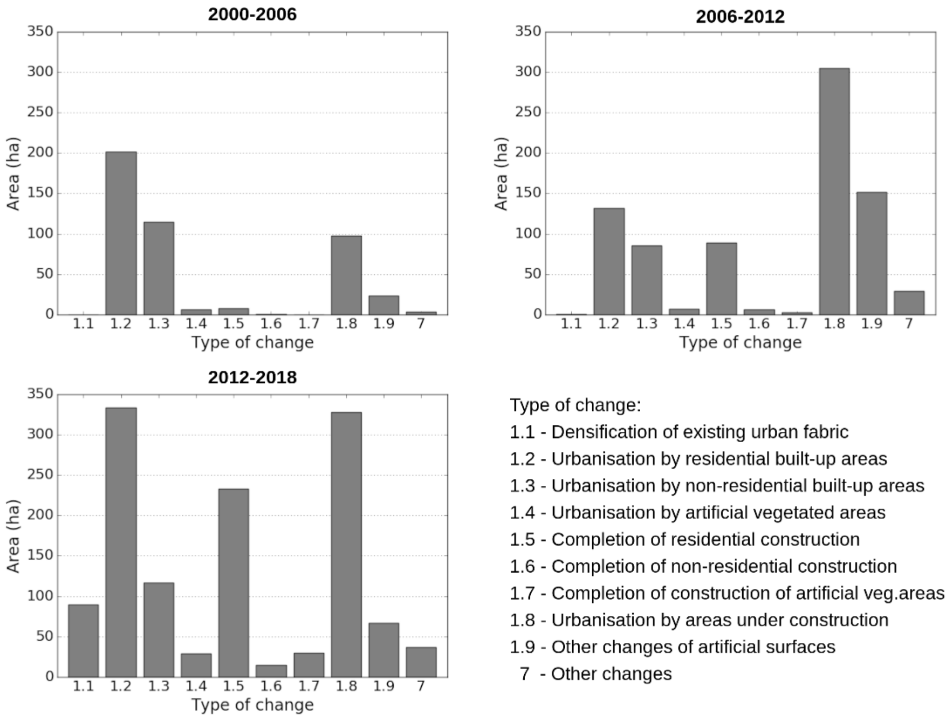

Fig. 3. *Absolute proportions of change types in the total area of changes in the Senec district in years 2000-2006, 2006-2012 and 2012-2018*

The analysis of gain and losses of LC classes between 2012 and 2018 (fig. 4) shows a visible decrease of more than 800 ha from the area of agricultural land (class 20000), while the classes of continuous and discontinuous urban fabric (11100, 11210, 11220) and industrial, commercial, public, military and private units (12100) recorded an increase in area. The class of construction sites (13300) recorded both an increase and decrease in area, with a positive net change of 18.6 ha. As the class of agricultural land lost the largest part of the area, we focused on the structure of contributors to the net change of this class. The agricultural areas disappeared mainly at the expense of the construction sites, but also the residential development and industrial, commercial, public, military and private sites were completed there. A very similar structure of landscape changes was identified in the years 2000-2006 and 2006-2012. During the entire period 2000-2018, almost 2000 ha of agricultural land decreased in favor of construction sites and built-up areas. On the contrary, more than 1000 ha of residential built-up areas, 316 ha of non-residential built-up areas and 366 ha of construction sites were added. Urban greenery with an area of 6 ha were created, while 10 ha of urban greenery disappeared.

Although the changes can be studied in more detail through a contingency table and a comparison of gains and losses of individual LC classes (e.g., in Pazúr and Kopecká 2015), this approach lacks the spatial aspect. Showing the spatial distribution of individual “from-to” transitions in the map by conventional methods is not possible, as the number of identified transitions ranges from tens to hundreds (Cebecauerová and Cebecauer 2005). Visualization of changes aggregated into the meaningful groups can provide essential information about their spatial distribution and potential driving forces. In the proposed conversion table for the UA 2006 legend, nine types of changes illustrate in more detail the process of urbanisation, which is expressed in the standard conversion table for the second level of CLC by one type of change.

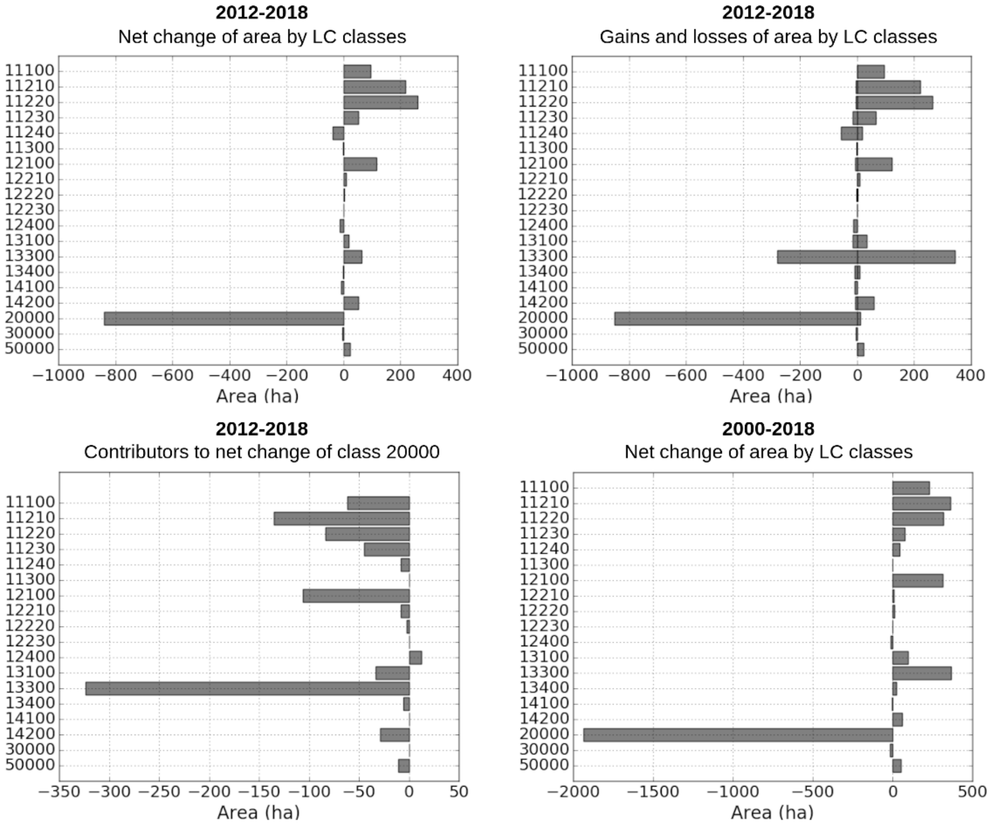

Fig. 4. *Net change of area by LC classes, the gains and losses of area by LC classes and the contributors to net change of class 20000 in the Senec district in the years 2012-2018 and 2000-2018*

The results of the case study are in line with the results of other, broader focused studies. The shrinkage of agricultural land 2000 (arable land especially) in favour of construction was denoted by Pazúr and Kopecká (2015) as the most important change in the whole large urban zone of Bratislava in the years 2006-2012. Pazúr, Pazúrová and Oťahel (2019) also confirm the increasing dynamics of the transformation of agricultural, forestry and semi-natural areas into the built-up areas in the hinterland of Bratislava. According to their findings based on the CLC data, there were only small changes in 2000-2006, while in 2006-2012 the area of the changes increased. This trend is also obvious in the urbanisation processes throughout Slovakia, identified by Pazúr and Bolliger (2017) as follows: high urbanisation rates under socialism (1980-1990), a massive decline in the postsocialism (1990-2000) and European Union (EU) accession (2000-2006) periods and increasingly high urbanisation rates during the EU membership (2006-2012) period. Although the next period 2012-2018 has not yet been evaluated in the wider area, it appears that the process of suburbanisation continues, at least in the Senec district. However, there has been a partial slowdown in the establishment of new large-scale construction projects.

Spatial distribution and driving forces of the suburbanisation

The observed types of LC changes in the Senec district confirm manifestations of the suburbanisation process throughout the period 2000-2018. The municipalities with the most significant and spatially most extensive changes include the municipalities Chorvátsky Grob, Bernolákovo, Malinovo, Most pri Bratislave, Dunajská Lužná or Rovinka. To a greater or lesser extent, also municipalities from the central and southern parts of the district have also expanded. Only the northern part of the district lags behind the rest of the district in the intensity of changes, e.g., the municipalities of Blatné, Kaplna, Igram, Čataj, Boldog and Reca. There can be several reasons for this situation, the most likely being the lack of interest of potential new residents due to the relatively large distance from Bratislava and insufficient connection to the motorway. These conditions may change after the completion of the Blatné motorway junction, which may at least partially increase the attractiveness of the area for potential immigrants.

However, the analysis generally did not show a significant connection between the new residential development and the existing network of main roads or railways. Intensity of suburbanisation was not much larger along the first class roads than in the other parts of the district. This could be considered only in the southern part of the district around the road I/63, but in this area, as well as within the whole district of Senec, the impact of the immediate vicinity of Bratislava is a much more important factor. It is similar with the railway network, which is not yet a real factor that would attract residents to municipalities in its vicinity (Šolc 2018). On the contrary, logistics parks are usually located in places with good transport accessibility, such as the Logistics Park Senec.

The policy of mayors and municipal councils also plays an important role in localization of new residential projects, as it can either support or hinder the expansion of development. Čierna Voda, the local part of the Chorvátsky Grob municipality, is often referred to as an example of an uncontrolled suburbanisation process. In 2014, this part was the largest suburbium not only in the hinterland of Bratislava, but also largest in Slovakia (Šveda and Šuška 2014). Gradually, up to 10 new residential projects were added to this area, while the number of inhabitants of the municipality increased several times. During this extensive residential construction, almost no civic amenities were built in the municipality, which significantly reduced the quality of life of immigrants (Šveda and Šuška 2014, Ušák 2017). Recently, the situation has been at least partially solved by building two supermarkets, a small business centre, a kindergarten, a primary school, a Roman Catholic church and several playgrounds and parks. In addition, the ambulances of doctors and retirement home were opened here. Residents can also use the gradually increasing sections of cycle routes, either directly in the municipality or cycle route Jurava nearby. However, transport remains problematic, as the existing bus capacity is insufficient during the peak hours. Most of the new inhabitants commute to work with their own cars, which results in the formation of several-kilometre traffic jams in the direction to Bratislava, especially in the morning (Ušák 2017).

The spatial distribution of LC changes in Čierna Voda in three evaluated periods is shown in fig. 5. Several residential construction projects were gradually completed on the outskirts of the municipality. In addition, the Elán golf club was built on a larger area in the years 2000-2006. Orange colour on the map of 2012-2018 indicates the place of construction of the elementary school with kindergarten and adjacent recreational and sports park.

Another example of the local policy influence is the municipality of Hrubá Borša, which is one of the farthest municipalities from Bratislava, but has recently undergone the most significant changes thanks to the golf course project and related residential construction, with the built-up area increasing 2.5 times. On the contrary, in some municipalities, the new construction is scattered and does not form compact suburbs, e.g., in Ivanka pri Dunaji. According to Šveda (2019), in addition to the policy of local self-government, a fragmented ownership structure of land, unsettled land or land owned by a church or municipality can also be an obstacle to the large-scale development projects.

Regarding the future of suburbanisation within the Senec district, the recent reduction in the area of construction sites suggests that suburbanisation may not continue at such a rapid pace as in previous years. It is possible that the poor traffic situation and other mentioned disadvantages of living in an "urban sprawl" will reduce demand for new residential areas in the municipalities near Bratislava.

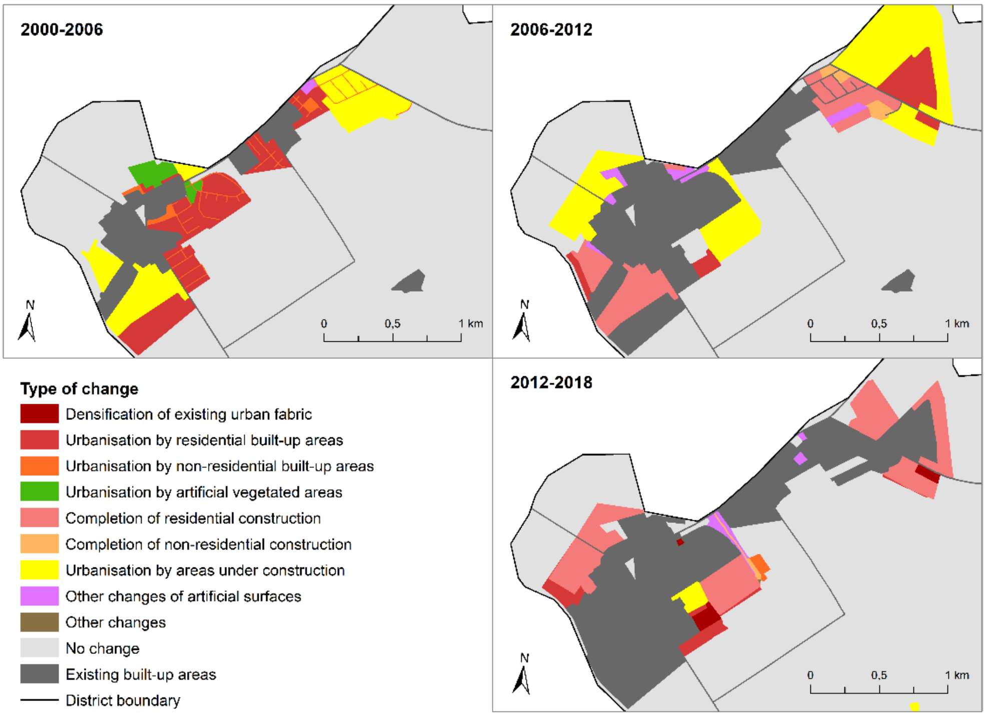

Fig. 5. *Land cover changes in the municipality Chorvátsky Grob, part Čierna Voda in the years 2000-2018*

The Change Detection Toolbox

All presented outputs were created using the CDT toolbox, which we also consider as the result of the study. The CDT toolbox has been used in several bachelor and master theses solved at the Department of Cartography, Geoinformatics and Remote Sensing at the Faculty of Natural Sciences, Comenius University in Bratislava. In addition to the monitoring of suburbanisation in the Senec district (Šolc 2018), the toolbox was used for the evaluation of the spatiotemporal landscape changes from digital photogrammetry data (Kollár 2019) or for the assessment of suburbanisation around Prešov on the basis of cadastral data (Maťašová 2018). Using the CDT tools and the old maps, development of the landscape over the longer time periods was also evaluated, such as the changes in historical structures of agricultural landscape in the region of Myjava (Moravčík 2019), the changes in vineyards in the district of Bratislava-Nové Mesto (Belčáková 2018) or the abandonment of agricultural land in the area of Hriňová (Švoňavová 2018).

Creating a conversion table of changes is the most time-consuming and laborious step in the CDT workflow. For standardized land cover nomenclatures such as the CLC or the UA, this step could be simplified using a pre-prepared conversion table. The conversion table was already proposed for the second hierarchical level of CLC, consisting of seven basic types of changes (Feranec et al. 2010). This table was later modified by Pazúr and Bolliger (2017), considering the forest disturbance as a process of tree removal. We have converted these tables to the format required by the Type of Change tool, and they are included in the CDT download package together with the proposed conversion table for the UA 2006 legend. However, it should be noted that for using this conversion table with the UA 2012 data layers, it is necessary to reclassify the LC classes of agricultural, natural and semi-natural areas to the less detailed UA 2006 legend. The proposal of an extended version of the conversion table for the UA 2012 legend is a part of the future development.

Conclusions

The paper evaluates the land cover changes caused by the suburbanisation in the district of Senec using the Change Detection Toolbox (CDT) in ArcGIS. The Senec district is located in the hinterland of Bratislava, the capital of the Slovak Republic. The change detection was based on the Urban Atlas (UA) 2006 and 2012 data layers as well as the other two layers capturing the land cover state in 2000 and 2018 according to freely available satellite images. The analysis of land cover changes throughout the period 2000-2018 showed that suburbanisation took place with the greatest intensity in the years 2006-2012, but the first large residential projects began to be built in the years 2000-2006. Gradually, these projects were completed and new ones were established at the same time. The most affected municipality by the new construction was Chorvátsky Grob, where up to 10 new residential projects were created, which led to many problems with civic amenities or transport. In addition to residential projects, the Logistics Park Senec was also built and the construction of the Bratislava D4/R7 bypass began. In the years 2012-2018, the intensity of suburbanisation decreased slightly. During the whole monitored period, all construction projects took up to 2000 ha of agricultural land.

To evaluate the changes in urban and suburban areas, a conversion table based on the UA 2006 legend was designed. Nine types of changes in artificial surfaces express individual processes of (sub)urbanisation such as densification of the existing urban fabric, construction of new residential and non-residential built-up areas, start and completion of construction. For the UA legend, such a table has not been published yet, and the changes were evaluated based on individual transitions or gains and losses of individual classes. The classification of changes into types allows a quantitative evaluation of processes, their spatial distribution and potential drivers. In the district of Senec, the proximity of Bratislava as a functional core proved to be the most important factor for the location of new construction. However, non-spatial factors such as local policy and land ownership also play an important role.

For the automated detection and evaluation of landscape changes based on vector layers, the Change Detection toolbox (CDT) was developed. While the Land Change Modeler software is designed for the raster data format, similar tools for the vector format have not yet been available. In monitoring local landscape changes, but also in global projects such as the Corine Land Cover (CLC) and the UA, vector layers are most often used. The need for automation increases with the number of time slices used. Increasing availability of the satellite image archives, as well as the regularly updated European archive of freely available Copernicus data and services, are driving the growth of similar studies.

CDT is a Python toolbox working within ArcGIS, the most widely used commercial GIS system. It consists of four tools that enable change detection based on vector input layers, classification of change types, determination of hierarchical level of change and basic statistical evaluation of changes. For the classification of changes, standardized conversion tables for the second hierarchical level of CLC, as well as the UA 2006 conversion table, are available as a part of a toolbox.

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References

BELČÁKOVÁ, L. 2018: *Zmeny krajinnej pokrývky vybranej časti územia Bratislava - Nové Mesto spracovaním starých máp so zameraním na vinohrady – bakalárska práca*. Bratislava (Comenius University in Bratislava, Faculty of Natural Sciences).

CAHA, J. 2018: Line of Sight Analyst: ArcGIS Python Toolbox for visibility analyses. *Geographia Cassoviensis*, 12, 5–15.

CEBECAUEROVÁ, M., CEBECAUER, T. 2005. Špecifické vizualizácie zmien krajinnej pokrývky ako nástroj poznávania krajiny. *Kartografické listy*, 13, 34-42.

CIEŚLAK, I., BIŁOZOR, A., SZUNIEWICZ, K. 2020. The use of the CORINE Land Cover (CLC) database for analyzing urban sprawl. *Remote Sensing*, 12, 282. DOI: https://doi.org/10.3390/rs12020282.

DRUGA, M., FALŤAN, V., HERICHOVÁ, M. 2015: Návrh modifikácie metodiky CORINE Land Cover pre účely mapovania historických zmien krajinnej pokrývky na území Slovenska v mierke 1:10 000 – príkladová štúdia hist. k.ú. Batizovce. *Geographia Cassoviensis*, 9, 17-34.

EEA 2006: *Urban sprawl in Europe. The ignored challenge.* EEA Report No. 10/2006. Copenhagen (EEA – European Environmental Agency).

EEA 2007: *CLC2006 technical guidelines.* Copenhagen (EEA – European Environmental Agency).

EC 2011: *Mapping Guide for a European Urban Atlas.* Luxembourg (EC – European Commission).

EC 2016: *Mapping Guide for a European Urban Atlas.* Luxembourg (EC – European Commission).

FERANEC, J., OŤAHEL, J. 2001: *Krajinná pokrývka Slovenska*. Bratislava (Veda).

FERANEC, J., HAZEU, G., CHRISTENSEN, S., JAFFRAIN, G. 2007: Corine land cover change detection in Europe (case studies of the Netherlands and Slovakia). *Land Use Policy*, 24, 234-247. DOI: https://doi.org/10.1016/j.landusepol.2006.02.002.

FERANEC, J., JAFFRAIN, G., SOUKUP, T., HAZEU, G. 2010: Determining changes and flows in European landscapes 1990–2000 using CORINE land cover data. *Applied Geography*. 30: 19-35. DOI: https://doi.org/10.1016/J.APGEOG.2009.07.003.

FERANEC, J., OŤAHEL, J., KOPECKÁ, M., NOVÁČEK, J., PAZÚR, R. 2018: *Krajinná pokrývka Slovenska a jej zmeny v období 1990-2012*. Bratislava (Veda).

GERARD, F., BUGAR, G., GREGOR, M., HALADA, L., HAZEU, G., HUITU, H. et al. 2010: Land cover change in Europe from 1950 to 2000 determined from aerial photography. *Progress in Physical Geography*, 34, 183-205. DOI: https://doi.org/10.1177/0309133309360141.

GORELICK, N., HANCHER, M., DIXON, M., ILYUSHCHENKO, S., THAU, D., MOORE, R. 2017: Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment*, 202, 18-27. DOI: https://doi.org/10.1016/j.rse.2017.06.031.

HUANG, H., CHEN, Y., CLINTON, N., WANG, J., WANG, X., LIU, C. 2017: Mapping major land cover dynamics in Beijing using all Landsat images in Google Earth Engine. *Remote Sensing of Environment*, 202, 166-176. DOI: https://doi.org/10.1016/J.RSE.2017.02.021.

KEYEL, A. C., REED, S.E., MCKENNA, M.F., WITTEMYER, G. 2017: Modeling anthropogenic noise propagation using the Sound Mapping Tools ArcGIS toolbox. *Environmental Modelling & Software*, 97, 56-60. DOI: https://doi.org/10.1016/J.ENVSOFT.2017.07.008.

KOLLÁR, D. 2019: *Časovo-priestorové zmeny štruktúry krajiny z dát digitálnej fotogrametrie – diplomová práca*. Bratislava (Comenius University in Bratislava, Faculty of Natural Sciences).

KOPECKÁ, M., ROSINA, K., OŤAHEL, J., FERANEC, J., PAZÚR, R., NOVÁČEK, J. 2015: *Geographica Slovaca 30: Monitoring dynamiky zastavaných areálov*. Bratislava (GÚ SAV).

KOPECKÁ, M., SZATMÁRI, D., SVIČEK, M. 2019: Hodnotenie zmien vo využívaní poľnohospodárskej pôdy v okresoch Pezinok a Senec v rokoch 2004 – 2018. *Geografický časopis*, 71, 121-140.

KOVÁCS, Z., FARKAS, Z.J., EGEDY, T. et al. 2019: Urban sprawl and land conversion in post-socialist cities: The case of metropolitan Budapest. *Cities*, 92, 71-81. DOI: https://doi.org/10.1016/j.cities.2019.03.018.

LIESKOVSKÝ, J., BEZÁK, P., ŠPULEROVÁ, J., LIESKOVSKÝ, T., KOLEDA, P., DOBROVODSKÁ, M. et al. 2015: The abandonment of traditional agricultural landscape in Slovakia – Analysis of extent and driving forces. *Journal of Rural Studies*, 37, 75-84. DOI: https://doi.org/10.1016/J.JRURSTUD.2014.12.007.

LU, D., MAUSEL, P., BRONDÍZIO, E., MORAN, E. 2004: Change detection techniques. *International Journal of Remote Sensing*, 25, 2365-2407. DOI: https://doi.org/10.1080/0143116031000139863.

MAŤAŠOVÁ, S. 2018: *Proces suburbanisácie v zázemí Prešova z hľadiska analýzy zmien údajov katastra nehnuteľností – bakalárska práca*. Bratislava (Comenius University in Bratislava, Faculty of Natural Sciences).

MIČIETOVÁ, E., KOŽUCH, M. ed. 2008: *Specializované informačné technológie v prírodovednom výskume: Geoinformarčné technológie*. Bratislava (Elita).

MORAVČÍK, F. 2019: *Zmeny priestorovej štruktúry krajinnej pokrývky vybranej časti kopaničiarskeho regiónu Myjavy – diplomová práca*. Bratislava (Comenius University in Bratislava, Faculty of Natural Sciences).

MORAVČÍK, F., BENOVÁ, A. 2020: Zmeny krajinnej pokrývky vo veľkých mierkach na vybranom území mestskej časti Bratislava – Devín s využitím starých máp. *Geographia Cassoviensis*, 14, 164-177. DOI: https://doi.org/10.33542/GC2020-2-03.

OŤAHEL, J., FERANEC, J., KOPECKÁ, M., FALŤAN, V. 2017: Modifikácia metódy CORINE Land Cover a legenda pre identifikáciu a zaznamenávanie tried krajinnej pokrývky v mierke 1:10 000 na báze príkladových štúdií z územia Slovenska. *Geografický časopis*, 69, 189-224. DOI: https://doi.org/10.1017/CBO9781107415324.004.

OŤAHEĽ, J., SOLÁR, V., MATLOVIČ, R., KROKUSOVÁ, J., PAZÚROVÁ, Z., IVANOVÁ, M. 2020. Prímestská krajina: Analýza premien vplyvom suburbanizačných procesov v zázemí Prešova. *Geografický časopis*, 72, 131-155. DOI: https://doi.org/10.31577/geogrcas.2020.72.2.07.

PAZÚR, R., KOPECKÁ, M., FERANEC, J. 2015: Changes of artificial surfaces of Bratislava in 2006 – 2012 identified by the Urban Atlas data. In Bičík, I. et al. eds. *Land Use/Cover Changes in Selected Regions in the World, XI*. Asahikawa (International Geographical Union Commission on Land Use/Cover Change: Hokkaido University of Education), pp. 37-42.

PAZÚR, R., BOLLIGER, J. 2017: Land changes in Slovakia: Past processes and future directions. *Applied Geography*, 85, 163-175. DOI: https://doi.org/10.1016/j.apgeog.2017.05.009.

PAZÚR, R., FERANEC, J., ŠTYCH, P., KOPECKÁ, M., HOLMAN, L. 2017: Changes of urbanised landscape identified and assessed by the Urban Atlas data: Case study of Prague and Bratislava. *Land Use Policy*, 61, 135-146. DOI: https://doi.org/10.1016/J.LANDUSEPOL.2016.11.022.

PAZÚR, R., PAZÚROVÁ, Z., OŤAHEL, J. 2019: Ako sa zmenila vidiecka krajina? Transformácia prímestskej krajiny z hľadiska zmien krajinnej pokrývky. In Šveda, M., Šuška, P. eds. *Suburbanizácia. Ako sa mení zázemie Bratislavy?* Bratislava (Institute of Geography, Slovak Academy of Sciences), pp. 56-81.

RAMÍREZ-CUESTA, J., MIRÁS-AVALOS, J., RUBIO-ASENSIO, J., INTRIGLIOLO, D. 2018: A Novel ArcGIS Toolbox for Estimating Crop Water Demands by Integrating the Dual Crop Coefficient Approach with Multi-Satellite Imagery. *Water*, 11, 38. DOI: https://doi.org/10.3390/w11010038.

RIGOL-SANCHEZ, J. P., STUART, N. A., PULIDO-BOSCH, A. 2015: ArcGeomorphometry: A toolbox for geomorphometric characterisation of DEMs in the ArcGIS environment. *Computers & Geosciences*, 85, 155-163. DOI: https://doi.org/10.1016/J.CAGEO.2015.09.020.

ROUX, C., ALBER, A., BERTRAND, M., VAUDOR, L., PIÉGAY, H. 2015: “FluvialCorridor”: A new ArcGIS toolbox package for multiscale riverscape exploration. *Geomorphology*, 242: 29-37. DOI: https://doi.org/10.1016/J.GEOMORPH.2014.04.018.

SINGH, A. 1989: Review Articlel: Digital change detection techniques using remotely-sensed data. *International Journal of Remote Sensing*, 10, 989-1003. DOI: https://doi.org/10.1080/01431168908903939.

STANKOVÁ, H., ŠOŠOVIČKOVÁ, L. 2013: Modelovanie a predikcia zmien krajiny s využitím údajov CORINE Land Cover na príklade územia zo severovýchodného Slovenska. *Kartografické listy*, 21(1), 47-59.

SZATMÁRI, D., KOPECKÁ, M., FERANEC, J. 2019: Verifikácia a kvalitatívne hodnotenie vrstiev Urban Atlas na území Slovenska. *Kartografické listy*, 27: 25-33.

ŠOLC, A. 2018: *Monitorovanie suburbanizácie v zázemí Bratislavy na podklade satelitných údajov: prípadová štúdia v okrese Senec – bakalárska práca*. Bratislava (Comenius University in Bratislava, Faculty of Natural Sciences).

ŠUŠKA, P.,ŠVEDA, M. 2019.: Suburbanizácia? In Šveda, M., Šuška, P. eds. *Suburbanizácia. Ako sa mení zázemie Bratislavy?* Bratislava (Institute of Geography, Slovak Academy of Sciences), pp. 1-19.

ŠÚSR 2019: Počet obyvateľov podľa pohlavia – obce (ročne). Bratislava (ŠÚSR). Retrieved from: http://datacube.statistics.sk/#!/view/sk/VBD_DEM/om7101rr/v_om7101rr_00_00_00_sk.

ŠVEDA, M. 2011: Suburbanizácia v zázemí Bratislavy z hl'adiska analýzy zmien krajinnej pokrývky. *Geografický časopis*, 63, 155-173.

ŠVEDA, M., ŠUŠKA, P. 2014: K príčinám a dôsledkom živelnej suburbanizácie v zázemí Bratislavy: príklad obce Chorvátsky Grob. *Geografický časopis*, 66, 225-246.

ŠVEDA, M. 2019.: Paneláky naležato? Bytová výstavba a jej priestorové formy v zázemí Bratislavy. In Šveda, M., Šuška, P. eds. *Suburbanizácia. Ako sa mení zázemie Bratislavy?* Bratislava (Institute of Geography, Slovak Academy of Sciences), pp. 20-55.

ŠVOŇAVOVÁ, K. 2018: *Opúšťanie poľnohospodárskej krajiny vo vybranej časti Hriňovej použitím starých máp – bakalárska práca*. Bratislava (Comenius University in Bratislava, Faculty of Natural Sciences).

UŠÁK, M. 2017: *Urbanistická analýza obce Čierna Voda se zaměřením na současné trendy v urbanismu a územním plánování– bakalárska práca.* Brno (Brno University of Technology Faculty of Civil Engineering).

ŽUBRIETOVSKÝ, L. 2016: *Vývoj nástroja na automatickú identifikáciu a hodnotenie zmien krajiny v prostredí ArcGIS – diplomová práca*. Bratislava (Comenius University in Bratislava, Faculty of Natural Sciences).

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