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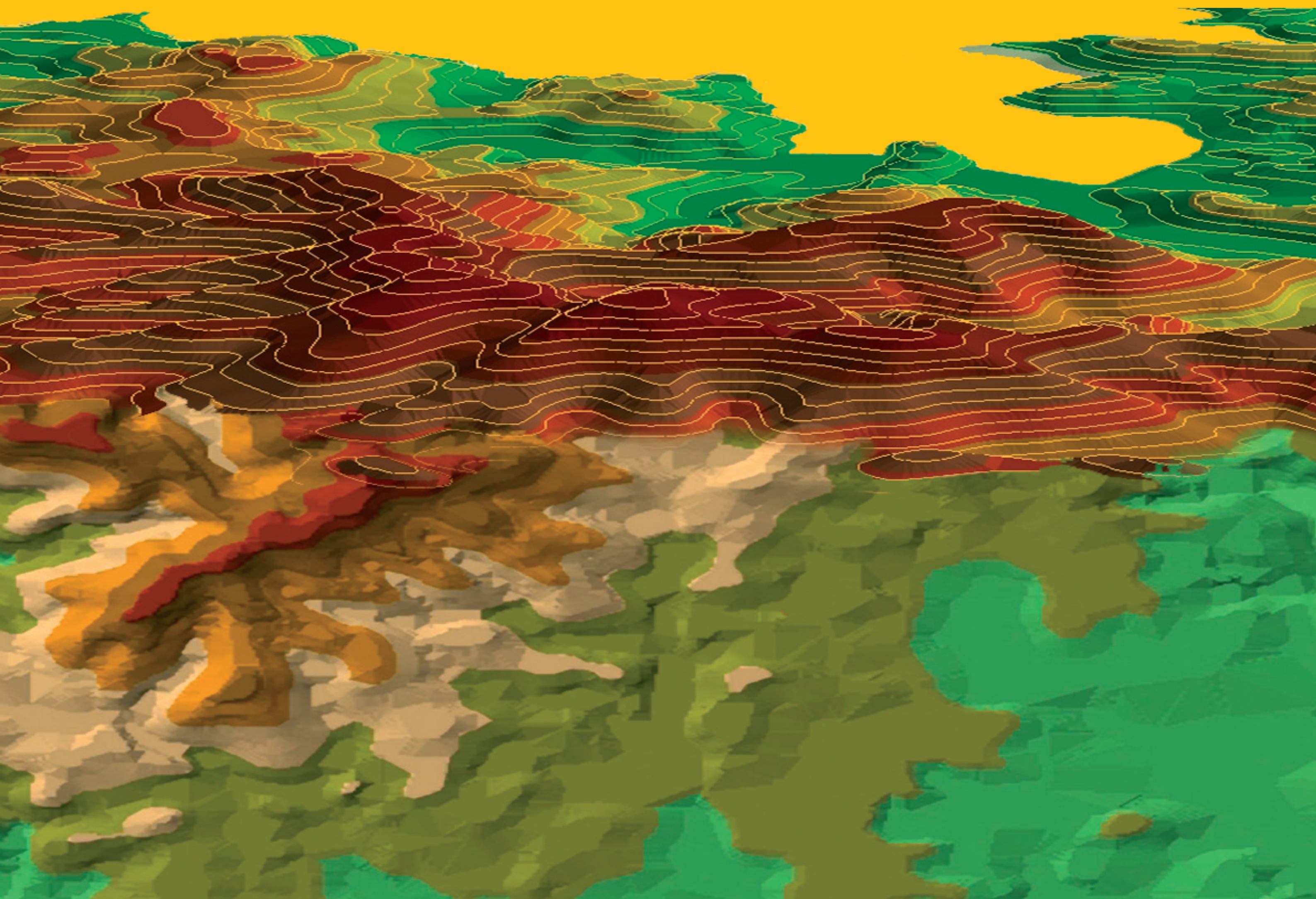

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Detection and visualisation of terrain edges in slope failures

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Abstract

Our aim was to develop a pixel-based methodology employing multiple terrain parameters for the semi-automatic identification of terrain edges. The procedure was applied to landform features associated with slope failures, operating on different resolutions of a digital terrain model (DTM). We intended to produce two outputs – grid maps base on: discrete data allowing precise identification and revealing a higher incidence of terrain edges than a hillshade map; floating point data visually highlighting terrain edges more sharply than a hillshade grid. The results showed that the grid maps generated by the new method: Binary Terrain Edges – BinT and Quality Terrain – QT exhibited more terrain edges than the hillshade map. The method demonstrated its robustness when used across three different resolutions of DTM. It was applied within the protection buffer zone of the overhead transmission powerline (OHL). Slightly more than half of the total of identified and manually digitised slope failures using the hillshade map supplemented with failures observed in QT may not necessarily be subject to field confirmation. OHL is a long-distance construction passing a variety of environments. Therefore, the detection of slope failures requires semi-automatic or automatic procedures to be costless and time-saving.

Keywords: Terrain edges, binary grid, quality terrain, pixel-based methods, digital terrain model, LiDAR

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1. Introduction

Slope failures have serious consequences for land cover and constructions (Aigbadon et al, 2021). A landslide hazard map or model produced using GIS technologies is usually a common tool used to mitigate or prevent slope movement (Liu et al., 2021). Verification of slope failures identified in digital products is routinely carried out in the field by geological experts, often in collaboration with geodesists (Prokešová et al., 2010; Podolszki et al., 2022). Today's technology makes it possible to accurately identify slope failures, even subtle ones, in detailed and accurate digital terrain models (DTMs) where field verification would not be necessary (Ortuño et al., 2017). The advantage of using hillshaded derivatives of DTMs is the visual highlighting of landforms that are difficult or impossible to identify from aerial photographs or field observations (Van Den Eeckhaut et al., 2007). However, many researchers still recommend selective field validation to improve the reliability of landslide mapping outputs, particularly when the datasets or the algorithms involved are untested in specific geological or environmental settings (Jaboyedoff et al., 2018).

Geohazards intersecting with technical and urban constructions may result in significant economic damages (Liščák et al., 2010). The Slovak republic has no national report accounting slope failures within urban structures or energy infrastructure. Strategies for landslide prevention are outlined in the "Program for the Prevention and Management of Landslide Risks (2014–2020)" (Ministry of the Environment of the Slovak Republic, 2018). An engineering geological survey conducted between 2018–2019 identified 13 sites with the most severe landslides, demanding considerable attention due to their associated risk to life and properties (Mašlár et al., 2020). Semi-automatic detection of landslides would accelerate the updating of current databases.

The research presented in the article deals with one of the project's objectives that was carried out in cooperation with the Nuclear Power Plant Research Institute (VUJE a.s.). The project purpose was to produce two outputs that would be useful for overhead power line (OHL) maintenance: 1) a method for classifying tree species – a model for predicting their growth under the power line; 2) a method for semi-automatic identification of terrain edges indicating the presence of slope failures. An area under investigation was a protection buffer zone of 100 m to each side from the transmission powerline. In the Carpathian Mountains of the Slovak Republic, OHLs are often located in steep and rugged terrain, usually covered by forests. This is also the case in this study. Therefore, the identification of slope failures requires specific procedures to make mapping efficient – fast and costless.

2. Theoretical background

2.1 Identification of slope failures features in high-resolution digital terrain models

A classification by Cruden & Varnes (1996) updated by the British Geological Survey (2024) defines the basic types of landslides: falls,

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topples, slides (rotational and translational) and flows. Landslides are characterised by the following features: crown, main scarp, top, head, minor scarp, main body, foot, tip, toe, surface of rupture, toe of surface of rupture, surface of separation, displaced material, zone of depletion, zone of accumulation, depletion, depleted mass, accumulation, flank, and original ground surface. A spatial model (Fig. 1a) shows the features – subtle landforms examined in this study and the features of the real landslide, one of several, which were identified in the study area (Fig. 1b). Although they span a few decimetres or metres, they play a crucial role in identifying an initial phase of slope movement.

Subtle landforms can be identified within high-resolution airborne Light Detection and Ranging (LiDAR) DTMs (Abellan et al., 2016; Mora et al., 2018; Chudý et al., 2018a,b; Martins et al., 2020). The main limitation lies in the point density of the LiDAR dataset (Pirotti & Tarolli, 2010). High-resolution DTMs enable the measurements of multi-temporal slope displacements (Fernández et al., 2017). The Unmanned Aerial Vehicle (UAV) is a relatively low-cost technology for obtaining detailed aerial images. The applicability of UAV data depends on the Structure-from-Motion (SfM) software processing of the photogrammetric material and the drone pilot's ability to navigate the UAV over the slope failure in complex natural settings (Giordan et al., 2020). It allows regular surveys to produce a time series of high-resolution images (Rossi et al., 2018; Mercuri et al., 2023). Even, Digital Surface Models (DSMs) which are produced in detail and high accuracy allow a series of measurements of slope failures variables to compute volumetric changes (Turner et al., 2015; Du et al., 2023). The most detailed mapping and assessment of spatio-temporal morphological change in any area is provided by combining data from geomorphological field surveys, LiDAR and UAVs (Borrelli et al., 2019). However, applying this approach on a wide scale is technologically demanding and takes a long time to process heavy datasets.

Landforms such as gullies, dunes, lava fields and landslides, all have similar features exhibiting high roughness contrast to the surrounding terrain. Thus, terrain roughness is an important variable to capture these features in DTMs (Korzeniowska et al., 2018). It is formed by sharply curved terrain edges. They are defined as significant local changes which are found on the border between two different regions. Edge detection is considered to be an initial step in the process of retrieving information from an image (Cesar & Costa, 1995). Edge detection techniques are generally divided into object-oriented and pixel-based methods, combination of both methods (Li & Wan, 2015; Zhao et al., 2017; Syzdykbayev et al., 2020) and spatial data mining methods (Hussain et al., 2013). Pixel-based and object-based classification methods differ in two aspects: classification units and classification features (Liu & Xia, 2010).

While a number of studies have demonstrated the advantages of object-based classification over pixel-based classification (Liu & Xia, 2010), less attention has been paid to the potential limitations of the image segmentation algorithm (Kampouraki et al., 2008). A main restriction of the pixel-based analysis is a lack of correspondence between landslide size and pixel size (Domènech et al., 2019). However, it can be overcome with additional data from LiDAR with a very high resolution (Chudý et al., 2019). Although pixel-based methods do not work with real objects, their advantage is the availability of a wide range of statistical operators in any GIS application (Hussain et al., 2013). This was a factor in the decision to use a pixel-based algorithm in this research.

2.2 Semi-automatic methods to identify terrain edges

Classifying landslide patterns from DTMs has been the subject of numerous studies (Razak et al. 2011; Al-Rawabdeh et al., 2016; Mărgărint & Niculiţă, 2017; Masruroh et al., 2023). Slope failures are usually manually digitised based on their visual interpretation from aerial photographs and subsequently confirmed by field surveys (Długosz, 2012). A hillshade map is commonly used to identify and delineate slope failures (Van Den Eeckhaut et al., 2005). However, it has not been proven to be sufficiently effective in identifying subtle landforms that do not cast enough strong shadows (Jagodnik et al., 2020; Jagodnik, 2024).

Current literature lacks approaches on semi-automatic classification specifically addressing subtle landforms of slope failures (Jagodnik, 2024). This procedure demands firstly, very precise DTM and secondly, a combination of diverse tools to extract these features from digital models (Mayoral et al., 2017; Lee et al., 2017; Lieskovský et al., 2022). Interpretation of the slope failures features facilitates the identification of their patterns. It is an essential input for machine learning algorithm or the development of spatial landslide models based on topographic zoning (Masruroh et al., 2023). Extraction of these features can be performed in eCognition Developer, a software development kit that uses an object-oriented approach to semi-automated image analysis (Shruthi et al., 2011). The authors noted that the accuracy uncertainty of the classified objects needs to be revalidated or corrected by other methods, and that the results also contain false positives. However, it should be noted that other methods may also produce false positives. Another popular method for detecting landform patterns in DTM is Geomorphon. It is a r.geomorphon tool that operates under Geographic Resources Analysis Support System (GRASS) GIS and Quantum (QGIS) GIS applications. The algorithm allows to recognise common local morphological elements such as flats, peaks, ridges, shoulders, spurs, slopes, hollows, footslopes, valleys, and pits (Jasiewicz & Stepinski, 2013). However, it is not designed to detect the subtle

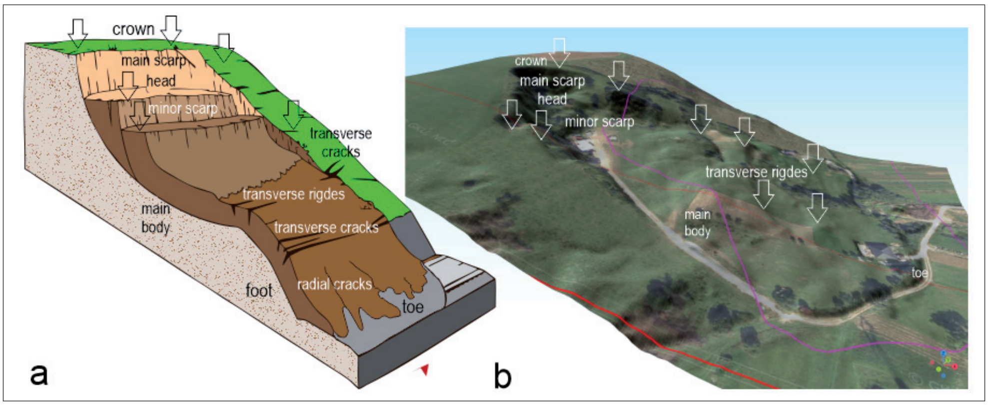

Fig. 1: A general model of a slope failure (a), a real landslide demonstrating the features investigated in this study (b)
Source: Author's conceptualisation (a), The Geodesy, Cartography and Cadastre Authority of the Slovak Republic: DMR5.0 (1 m) JTSK(JTSK03) and ortho-photomosaic, State Geological Institute of Dionýz Štúr: slope failures; modified by the author (b)

landforms of terrain edges on slopes. A method that was primarily, but not only, designed to detect subtle landforms developed Zhou et al. (2018). These performed multi-neighbourhood analysis to determine the edges of linear terrain features of ridge, shoulder, valley and foot-slope and defined a probabilistic visual descriptor for quantifying edge pixels. The technique of edge detection usually begins with the filtering to reduce data noise, followed by enhancement to identify changes in the intensity between two different regions and finishes with the detection of lines with strong edge content (Cesar & Costa, 1995). These methodological steps sketched a concept for a newly proposed method.

2.3 The aim

The aim of the article was to develop a methodology for semi-automatic identification of pixels interpreting sharply curved terrain edges of scarps, cracks and transverse ridges in the main landslide's body and its accumulation zone (Fig. 1a,b). We intended to develop an algorithm to detect pixels with "strong edge content", as defined by Cesar & Costa (1995), instead of lines, which are interpreted as vectors and are the output of the object-oriented methods. Terrain edges detected by the new method would contrast sharply with the smooth slopes around them.

A new method is designed to work with digital formats of a grid map based on:

- Discrete data allowing precise identification and revealing terrain edges of subtle landforms, and the main output is binary grid of terrain edges (Binary Terrain Edges, BinTerrain, BinTE);
- Floating-point data visually highlighting terrain edges, and the main output is grey-shaded grid of terrain edges (Quality Terrain, QTerrain, QT).

In terms of the method applicability, we assume that:

- Both grid maps produced by the new method exhibit more terrain edges than could be detected in the hillshade map;
- It could be applied on DTMs with different resolutions, allowing objects to be studied at different scales;
- The usability of the grid map on steep slopes above 25° may be limited due to the low contrast between the terrain edges of slope failures and other landforms in their vicinity.

3. Data and methods

3.1 Study area

The wider area of slope failures alongside the OHL under investigation is located in the north-western part of the Slovak Republic near the towns of Považská Bystrica and Žilina and covers an area of 10,897 hectares. The terrain edge survey was carried out within the OHL buffer zone, which is 100 metres on either side of the transmission line, with a total length of 55 kilometres and an area of 1,090 hectares (Appendix 1). The geological environment is an important indicator of potential slope failures and they were identified on a public 1:50,000 scale map (Šimeková et al., 2006) within the wider study area (Fig. 2, black line). Their coverage was evaluated using QGIS application. Slope failures occurred over 470 ha (4%) of the wider area. Of these landslides, 28 ha were active, 226 ha potential, and 216 ha were stabilised forms. The Quaternary Geological Map of the Slovak Republic (Maglay et al., 2011) indicated two landslides (Fig. 2, red line). The presence of slope failures was the main criterion for the selection of study sites and the production of a high resolution DTM used for terrain analysis.

The proposed method was applied to three sites, designated A, B and C, and located in different geological formations and natural environments (Tab. 1). Sites A and B are landslides and they were chosen to demonstrate the efficiency of the method on different slopes. Site C demonstrates the applicability of the method on different DTM resolutions. Extra dense LiDAR data were not available for sites A and B. Therefore, site C was considered for the investigation. It is U-shaped gully with minor scarps on its banks and exposed bare substrate in its upper parts. This is the case of the morphological structure that could pose a potential risk for the development of deep-seated slope slides. Although this is not the case at the study site, as noted by the authors (Parkner et al., 2007), it is important to identify and monitor gullies in certain landslide-prone areas. Since site C is not the landslide, the results are presented in the appendix.

3.2 Data acquisition

The maps used in the research were obtained from public repositories. Digital terrain models were generated from DMR3.5 and DMR5.0 datasets which are freely available at public portals (The Geodesy, Cartography and Cadastre Authority of the Slovak Republic, 2023a, b, c). DMR5.0 is a product of high-resolution LiDAR with a point cloud density of 5 points/pixel with overall vertical accuracy equal to or less than 0.25 metres, and horizontal accuracy equal to or less than 0.50 metres (The Geodesy, Cartography and Cadastre Authority of the Slovak Republic, 2023c). DMR5.0 covers the full length of the OHL construction. DMR5.0 with a resolution of 1 metre per pixel was used in pivotal results detailing the subtle landforms of slope failures. The declared resolution of DMR5.0 is considered sufficient to detect terrain edges, as confirmed by other studies (Azizi et al., 2014; Ortuńo et al., 2017).

Further, an extra dense LiDAR point clouds were provided by VUJE a.s. and captured were from a helicopter using the RIEGL VP-1 LiDAR scanner and acquired in the period between April

Site	A	B	C
Geomorphological units[(a)]	Rajecká Kotlina Basin, a subunit of Žilinská Kotlina Basin	Lučanská Malá Fatra Mts., a subunit of Malá Fatra Mts.	Podmanínska Pahorkatina Upland, a subunit of Považské Podolie Valley
Regional geology[(a)]	Inner Carpathian Palaeogene	Core Mountain Range	Klippen Belt Mountain Range (Puchov section)
Bedrock[(a)]	Deluvial-polygenetic sediments: clayey-clayey and sandy slope clays	Gutenstein beds – Gutenstein (Annaberian) limestones: dark grey and black coarse-grain, layered, worm-like limestones; Ramsar dolomites: grey layered dolomites	Sandstones, silts, calcareous claystones, laminated silts and sills, and conglomerates
Clime-geographic type[(a)]	Basin climate, slightly cool	Mountainous climate, cold	Mountainous climate, moderately warm
Annual rainfall interval [mm][(a)]	600–850	800–1100	600–850
Annual air temperature (1961–1990) average [°C][(a)]	7.5	6.5	7.5
Slope mean[(b)]	9°	18°	9°

Tab. 1: Geomorphology, geology and climate of the study sites
Sources: (a) State Geological Institute of Dionýz Štúr: geomorphology, geology and bedrock, climate, rainfall and temperature, (b)The Geodesy, Cartography and Cadastre Authority of the Slovak Republic – DMR5.0 (1 m) JTSK(JTSK03): slope, modified by the author

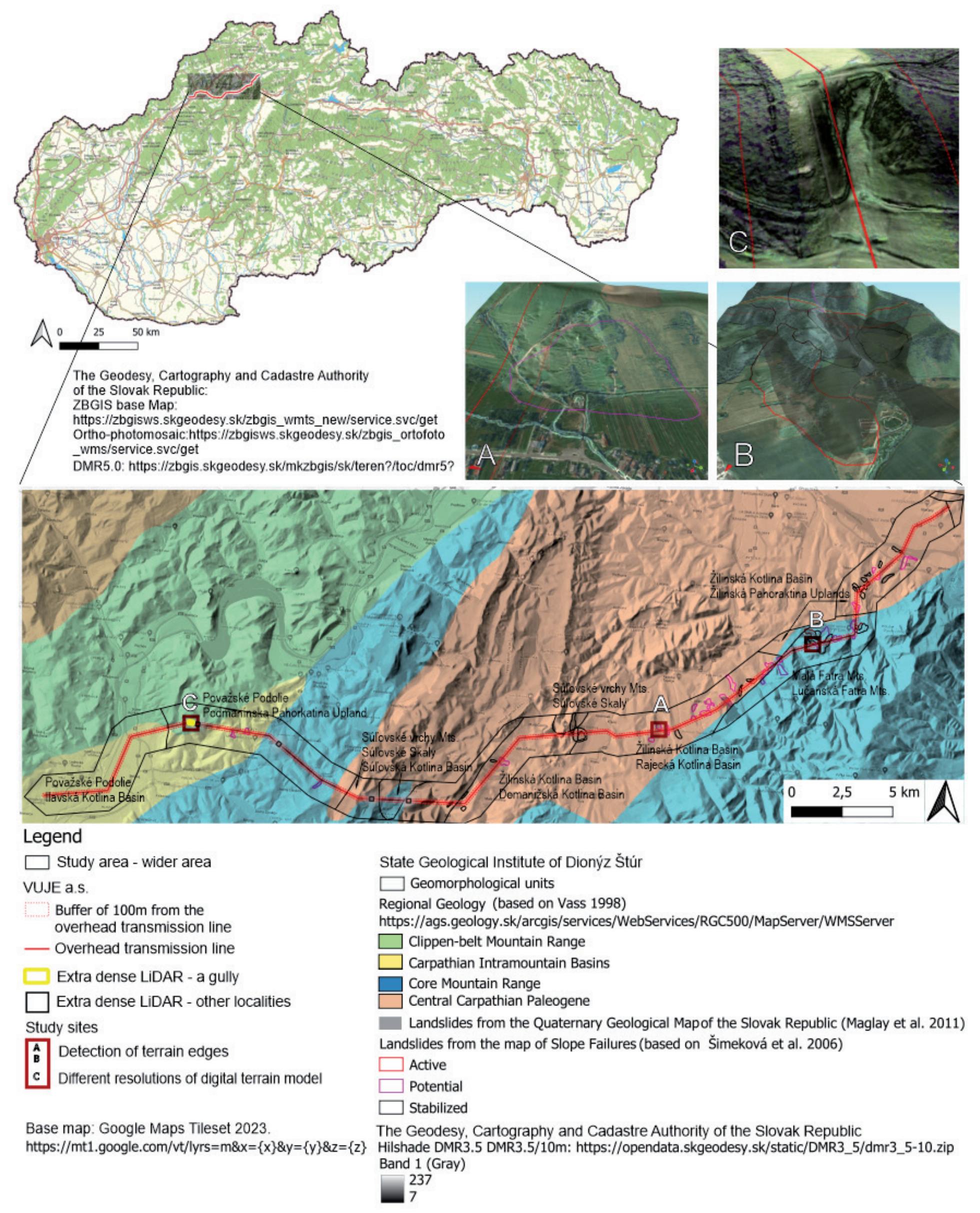

Fig. 2: The study area in the Slovak Republic and sites A, B and C
Source: VUJE a.s.: overhead transmission powerline, poles and protection zone, State Geological Institute of Dionýz Štúr: slope failures, regional geology and geology, The Geodesy, Cartography and Cadastre Authority of the Slovak Republic: Hillshade DMR3.5, Google Maps Tileset, modified by the author

and June 2023. RIEGL VP-1 had minimum scanning range of 5 m, accuracy 15 mm, precision 10 mm, maximum effective measurement up to 750,000 meas.s^{-1} (820 kHz PRR & 330° FOV), laser pulse repetition mode up to 820 kHz, near infrared laser wavelength, echo signal density for each echo signal high resolution, laser beam divergence 0.5 mrad. A point density varied from 484 PPSM (points per square metre) for all returns to 254 PPSM for the last returns to assess the applicability of the proposed method at sub-metre resolution. The LAS files were converted to the LAZ format, following the procedure published by Chudý et al. (2019). LAStools application was used to isolate ground return points. These points were converted to the vector format, and a fine-scale DTM was created using the TIN interpolation module in geographic information system (GIS) application. Using the original quarter mm (0.00025 metre) resolution of the LAS x,y,z tuples, a very high resolution DTM was produced at 0.15 metres per pixel. The original LAS format was projected in the S-JTSK [JTSK03] / Krovak East North (EPSG:8353) coordinate system.

VUJE a.s., provided also information about the OHL construction, its buffer zone of protection (100 m) and poles of the high voltage power line.

The datasets were processed using QGIS 3.28.10-Firenze, licensed under the GNU General Public License, and LAStools-a LiDAR processing software (version 220613, unlicensed). Spatial visualisations of subtle landforms were processed using the QGIS2threejs exporter plugin (QGIS Python Plugins Repository, 2022) and the EPSG 5514 coordinate system was set-up to process and render outputs.

3.3 Manual digitisation of slope failures in a hillshade map

Manual delineation of slope failures using a hillshaded map is a conventional technique applied in many recent studies (Van Den Eeckhaut et al., 2005; Długosz, 2012). We digitised slope failures in locations where we could visually detect terrain edges of subtle landforms indicating slope failures. Number and area [ha] were evaluated using the Field Calculator in QGIS.

3.4 New method – morphometric variables used to identify terrain edge

Local primary morphometric variables allow the detection of subtle landforms. They are calculated based on their immediate surroundings, derived directly from the DTM without additional input, and can be calculated independently of the wider area represented.

Slope is one such variable. It is a derivative of altitude (first derivation), measuring the maximum change in elevation relative to the distance between a cell and its eight neighbours (Barbosa et al., 2021). The slope gradient plays a pivotal role in movement tendencies. Slopes prone to landslides are expected to be predominantly between 30° and 45° (Guthrie & Evans, 2004) or between 15° and 25°, while those above 25° commonly experience shallow slides (Zęzere, 2002; Frattini et al., 2004). In the detection of landslide topography, slope is commonly fused with other elevation derivatives (Berti et al., 2013; Mora et al., 2018).

Terrain roughness, an efficient way to differentiate various landforms, displays elevation variability within a defined radius but it is highly sensitive to scale (Schillaci et al., 2015). Maximum curvature of the terrain was computed, rather than the terrain roughness, for the purposes of this research. Curvature is a second derivation of altitude. It highlights the convexity or concavity of the terrain. Positive values indicate convex, negative concave and zero values indicate planar landforms on slopes (Evans & Cox, 1999; Shary et al., 2002; Wilson, 2012). Local directions of maximum curvatures indicate the steepest variation of the surface normal (Alliez & Desbrun, 2002). Maximum curvature is an attribute that is very powerful in delineating defects and defect geometries (Roberts, 2001). The SAGA module of Terrain Analysis – Morphometry: Slope, Aspect, Curvature module was used to calculate maximum curvature and slope (SAGA-GIS Tool Library Documentation, 2001).

Sky view factor is a solar variable that is the secondary morphometric variable calculated to quantify interactions between the Earth's surface and the atmosphere (Wilson, 2012). These variables, interpreted in raster formats as shaded terrain, emphasise the brightness and contrast of landform discontinuities. The sky view factor visualises micro-landforms regardless of their orientation to the cardinal points. Diffuse light overcomes directional problems associated with hill shading (Kokalj & Somrak, 2019), and when combined with slope parameters, shaded terrains exhibit distinct terrain edges (Mayoral et al., 2017). In this study, we applied the sky view factor (SAGA-GIS Module Library Documentation v2.2.0, 2008), which ranges from 1 for completely unobstructed surfaces to 0 for completely obstructed surfaces (Harris & Baird, 2018). The search radius was set to 100 metres for the LiDAR DMR3.5 and 5.0, and 5 metres for the extra dense LiDAR data.

3.5 New method – calculation of terrain edge

3.5.1 A grid map based on discrete data

While the proposed method is pixel based, then terrain edges were evaluated in a grid form as pixels and not as vector lines. To identify the discontinuities in the terrain, the raster calculator was employed in operations on raster to multiply the slope and sky view factor grid layers. Maximum curvature values were displayed using a discrete colour ramp and interpreted within quantile ranges, typically used for ordinal data ranking within categories (GISGeography, 2023). Thresholding is common procedure in terrain analysis and its output is a binary classification in which data values above certain thresholds can be identified as target features (Zhou et al., 2018). Thus, values of the class representing the most convex landforms (higher than 0.0496 in this study) were used to compute a binary grid "BinaryMaximumCurvature". Further, the binary grid was subtracted from the "Slope" grid, multiplied by "SkyViewFactor" and saved as "TerrainEdges". This mathematical operation simply removes repetitive, and therefore redundant pixels (ARCGISpro, 2023).

A pseudo formula of the calculation follows:

OutputRaster("TerrainEdges") =

= Raster("Slope" * "SkyViewFactor") – Raster("BinaryMaximal Curvature")

The output of "TerrainEdges" was again interpreted with discrete symbology using quantile distribution values. Then it was reclassified to a binary grid using a threshold of the class with the highest values (higher than 0.0310 in this study) representing terrain edges. The output was saved as "BIN_TERRAIN_EDGES" (BinTE). This is the first product of the proposed methodology. A visual comparison reveals a lear distinction between the "BinaryMaximalCurvature" and "BIN_TERRAIN_EDGES" grids. BinTE contains less pixels but matches better terrain edges (Fig. 3).

3.5.2 A grid map based on floating-point data

To create a training dataset for the supervised classification in the next step, a raster was converted to a vector format of an ESRI shapefile using the Polygonise function. Further adjustments were made to remove redundant data, which means areas smaller than 4 m^2, consisting of three adjacent pixels in each direction. A vector output of "BIN_Terrain_Edges_4px" was created. In the extra dense LiDAR dataset, polygons with an area of 0.0225 m^2 were removed. Polygons derived from the DMR3.5 derivative were not adjusted due to the relatively small study area (a slope failure in study area C was up to 4 ha), which did not allow the removal of any pixels from the 10m/px DTM to maintain output accuracy. The main purpose of this step was to create a training vector dataset that best fits the target shapes of a pattern of terrain edges specific to the landforms being investigated. However, if it is necessary to preserve detailed terrain edges for any research purposes, this pixel removal step can be omitted.

SAGA Supervised Classification module (SAGA-GIS Tool Library Documentation v2.2.0, 2005) was employed to generate a "QUALITY_TERRAIN"(QT) – a floating-point raster that simulates shaded terrain and visually emphasises sharp, convex terrain edges indicating slope failures. QT is the second output of the proposed methodology. The process of the SAGA Supervised Classification involved a grid of "Slope" multiplied by "SkyViewFactor". Statistics were loaded from "BinaryMaximumCurvature". The training class was set up as a single value column, representing a specific target shape to be highlighted as the main output of the grey shaded grid. Chosen was the minimum distance method with the probabilistic reference set to relative. The default thresholds for distance, angle and probability were maintained default. The intricate shapes of the polygons "BIN_Terrain_Edges_4px" derived from three different sites (A, B, and C), are anticipated to exert an influence on each single result of the supervised classification of "QUALITY_TERRAIN".

The Supervised Classification is primarily a tool designed to categorise land cover based on spectral imagery, using training sites of known land cover and user-defined land cover. It classifies pixels by grouping them into classes according to the spectral data of the training site pixels (SAGA-GIS Tool Library Documentation v2.2.0, 2005). The intended usage for this research was different. We did not expect to produce an exact classification. We anticipated to get a range of values which could be divided into two groups. One group indicated a high level of confidence and reliability in the final output grid, while the other, with values close to zero, indicated a high level of uncertainty. Cesar & Costa (1995) defined edges as significant local changes at the border of different region.

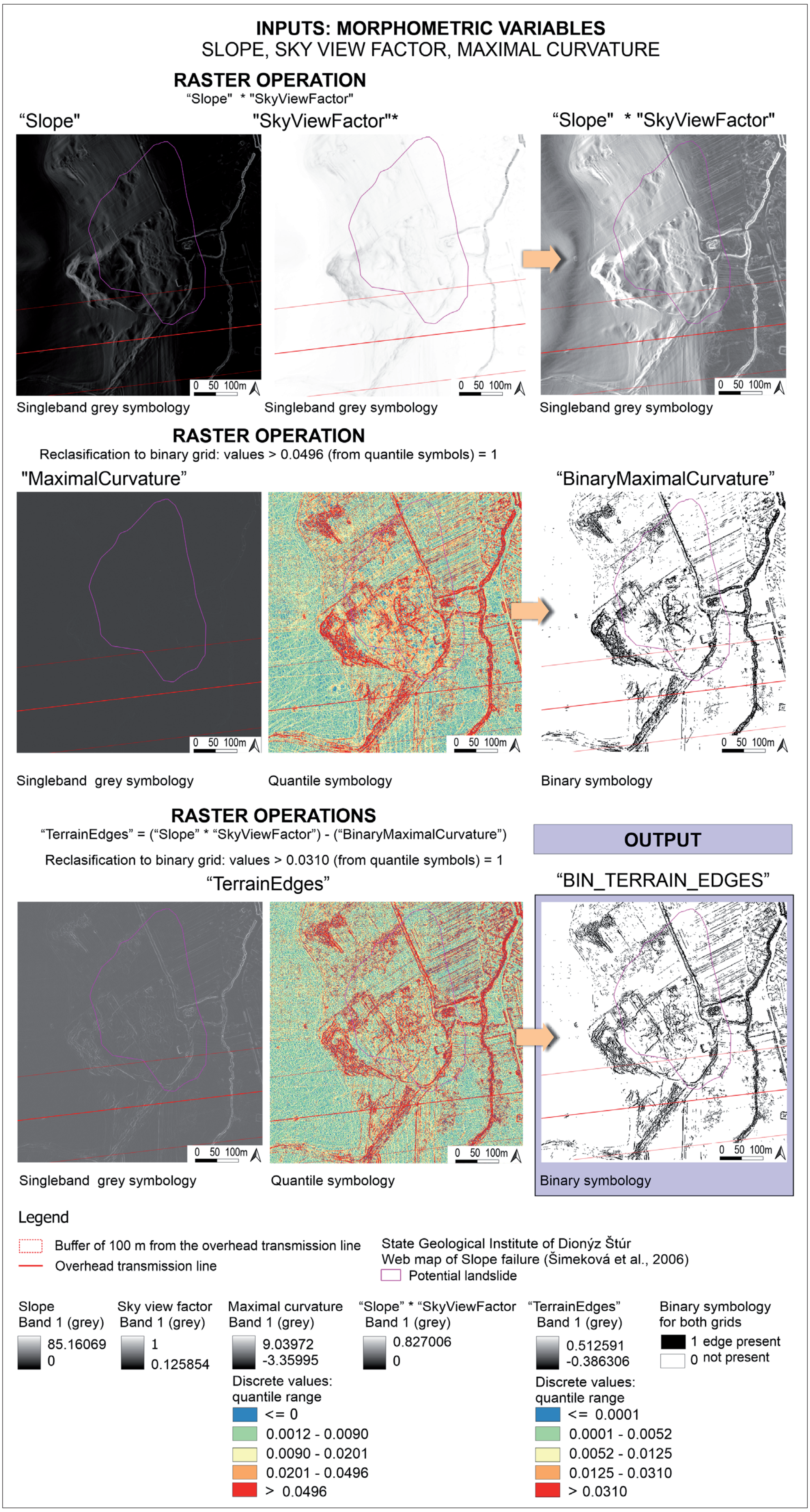

Fig. 3: Site A: process of calculation of a binary grid representing discontinuities in the terrain – terrain edges symbolised with value 1
Source: VUJE a.s.: overhead transmission powerline, poles and protection zone, The Geodesy, Cartography and Cadastre Authority of the Slovak Republic: DMR5.0 (1 m) JTSK(JTSK03), State Geological Institute of Dionýz Štúr: slope failures, modified by the author

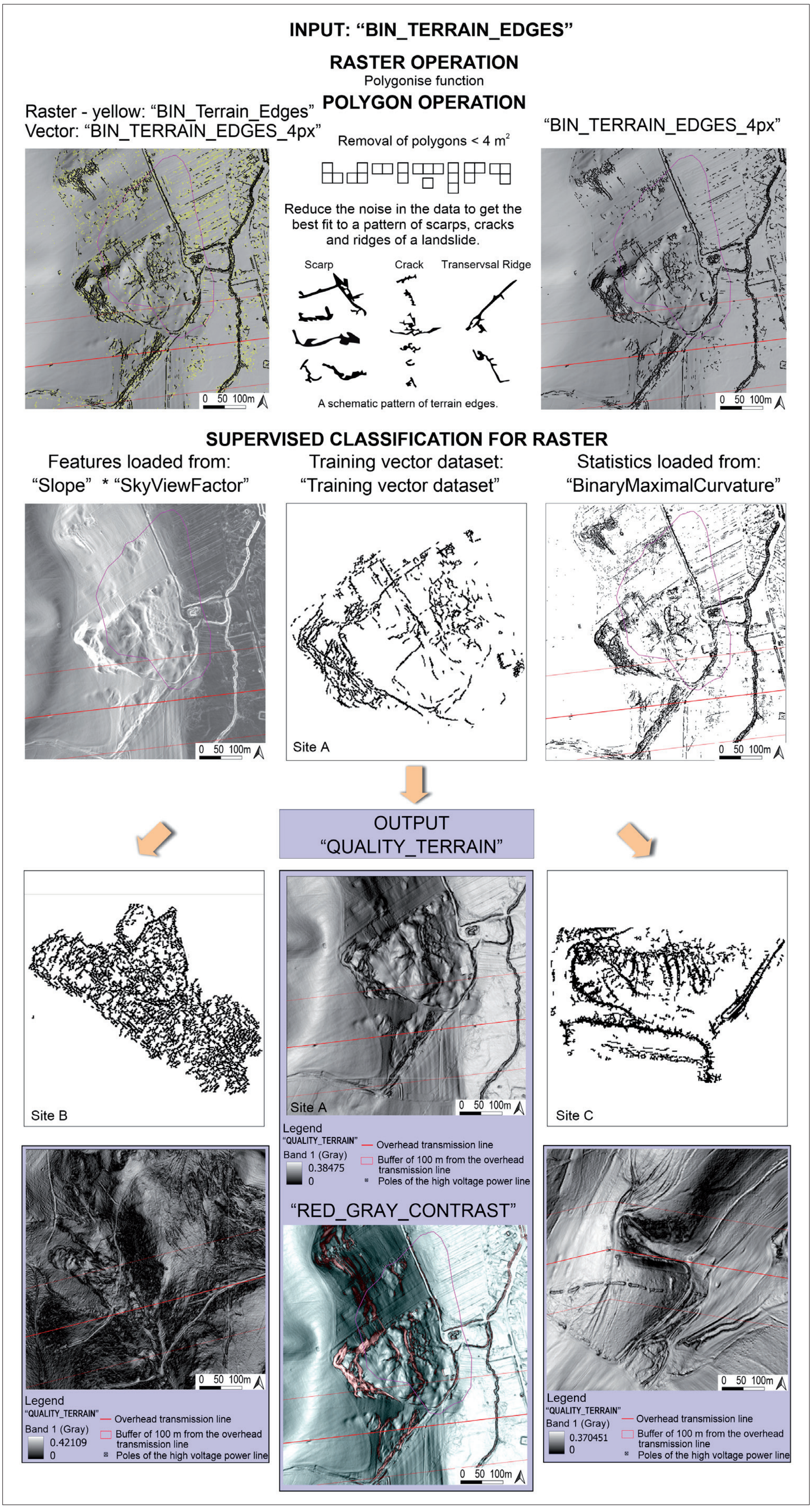

Fig. 4: Site A: process of calculation of a floating-point based grid representing discontinuities in the terrain – terrain edges (upper part). Sites A, B, C: outputs of the supervised classification (lower part)
Source: VUJE a.s.: overhead transmission powerline, poles and protection zone, The Geodesy, Cartography and Cadastre Authority of the Slovak Republic: DMR5.0 (1 m) JTSK(JTSK03), State Geological Institute of Dionýz Štúr: slope failures, modified by the author

Thus, the group of values close to zero represented discontinuities in the terrain – terrain edges on the slopes. These features differed significantly from their surroundings. The classification algorithm categorises them as areas of lower quality due to their uniqueness, higher uncertainty or greater distance from the class centroid within the dataset. On the other side, higher values indicated closer proximity to the centroid and a stronger association with a particular class.

As an experiment, we merged the "QUALITY_TERRAIN" grids from sites A, B and C into a virtual raster (QGIS Python Plugins Repository, 2021) with three separated bands of RGB spectrum. A single virtual layer was a pointer to merged grids. The multi-band symbology of the merged output "RED_GRAY_CONTRAST" visualised terrain edges in contrasting colour – red against other grey-shaded terrain. The symbology settings of the output raster marked the first band as the second and the second and third as the third band of RGB to produce a red-grey colour contrast. Other settings included a normal blend mode, brightness set to 15, gamma set to 1, saturation set to 20 and other parameters left at their default values (Fig. 4).

3.6 Evaluation of terrain edges in derivatives of digital terrain models

3.6.1 Comparison of shadows casted by terrain edges in a hillshade map with QTerrain

Shadows casted by terrain edges were compared within three study sites (A, B and C)

The first, "QUALITY_TERRAIN" raster was examined against a "HILLSHADE" raster and the results were compared and evaluated [ha] per each 25 ha of the study site. Basic unit that was used for evaluation is a pixel of size of one square metre (DMR5.0).

A pseudo formula of the calculation follows:

Sites A, C:

(("QUALITY_TERRAIN@1">=0.06) ^ ("QUALITY_TERRAIN@1"<=0.06)) * 1

(("HILLSHADE@1">=110) ^ ("HILLSHADE@1"<=110)) * 1

Site B:

(("QUALITY_TERRAIN@1">=0.06) ^ ("QUALITY_TERRAIN_B@1"<=0.06)) * 1

(("HILLSHADE_B@1">=190) ^ ("HILLSHADE@1"<=190))

Reclassification thresholds represent the values of the darkest shadows and were taken as the best result from the experimental testing of the appropriate value.

The second, a longitudinal and a transversal profiles were constructed across each slope failure within the study site. Terrain edges are inherently presented in the "QUALITY_TERRAIN", while in "HILLSHADE" they were identified using an edge detection algorithm from the SAGA-GIS Wombling Edge Detection module, applied with default parameters (SAGA-GIS Module Library Documentation v2.2.1, 2015). Spatial Wombling is an algorithm used to detect edges in a two-dimensional space (Strydom & Poisot, 2023). Vectorised polygons of terrain edges of "QUALITY_TERRAIN", and edges detected using the Wombling algorithms in "HILLSHADE" were intersected with a terrain profile created from DMR5.0. The procedure applied qProf plugin 0.5.1 (QGIS Python Plugins Repository, 2023). A length [m] of terrain edges was evaluated.

3.6.2 Evaluation of slope failures and terrain edges along the OHL construction

Slope failures which were difficult to recognise in "HILLSHADE" were additionally digitised using "QUALITY_TERRAIN". It does not mean that we were not able to see these subtle landforms in "HILLSHADE" but they did not cast enough strong shadows to identify them as terrain edges.

We compared the number and area [ha] of slope failures identified in "HILLSHADE" and "QUALITY_TERRAIN" and categorised them into three groups: slope failures not requiring field confirmation that were clearly visible in "HILLSHADE"; slope failures not requiring field confirmation that were clearly visible in "QUALITY_TERRAIN"; and slope failures requiring field confirmation. Although terrain edges were present, these we were not able to align to typical landslide features defined in Figures 1a and 1b. The presence of all digitised slope failures in the vicinity of the poles of the high-voltage power line was also recorded and evaluated.

BinTE contains more data about possible terrain edges as a binary grid of shadows casted by terrain edges of QT. Therefore, terrain edges were highlighted in BinTE by in red colour to demonstrate a pattern of subtle landforms typical for slope failures for each individual locality. Pattern of subtle landforms typical for slope failures could be used in the future to train a learning machine.

Enumeration of all possible slope failures within the extensive study area was not the primary objective of this article. The results of this methodological step only illustrate the potential applicability of the new method in practice. Graphical outputs of this methodological step are presented in the appendix.

4. Results

4.1 Evaluation of slope failures in a hillshade map

Totally, 22 slope failures was visually identified and manually delineated using "HILLSHADE" in the area along the OHL construction. These were supplemented with slope failures identified in "QUALITY_TERRAIN". Therefore, are interpreted in a map all together in the further results (4.3).

4.2. Evaluation of terrain edges in a hillshade map compared with QTerrain

Terrain edges are visible in both grid maps based on floating-point data. Undullating terrain and the main scarp are clearly visible in both "HILLSHADE" (Fig. 5 A-I., B-I.) and "QUALITY_TERRAIN" – the product of the new method (Fig. 5 A-II., B-II.). However, the grey scale grid in Figure 5 A-II. and B-II. clearly interprets even small scarps and the contrast in the grey shading depicts undulated terrain in the transport zone of the landslide. The difference is exactly illustrated in the reclassified greyscale maps into binary grids of "HILLSHADE" (Fig. 5 A-III., B-III.) and "QUALITY_TERRAIN" (Fig. 5 A-IV., B-IV.). Shadows casted by terrain edges were present at least twice more in "QUALITY_TERRAIN" against "HILSHADE" in case of site A (Tab. 2, Fig. 5 A-III. and A-IV.) while about fifty times more of shadows were detected "QUALITY_TERRAIN" against "HILSHADE" in site B (Tab. 2, Fig. 5 B-III. and B-IV.). Site A exhibited lower difference in the presence of terrain edges shadow evaluated in the "HILLSHADE" and "QUALITY_TERRAIN" against site B (Tab. 2, Figs. 6 and 7). On the other hand, the proposed method had better efficiency on site B where the presence of terrain edges was circa seven times higher in "QUALITY_TERRAIN" against "HILLSHADE" while shadows casted by terrain edges exhibited similar area in both binary grids in case of site A (Tab. 3). Results of site C demonstrating visual comparison are presented the appendix (Appendix 2).

Spatial visualisations created from DMR5.0. of "HILLSHADE" and "QUALITY_TERRAIN" overlapped with ortho-photomosaic of sites A and B demonstrated markedly higher contrast of terrain edges of landslides in "QUALITY_TERRAIN" against

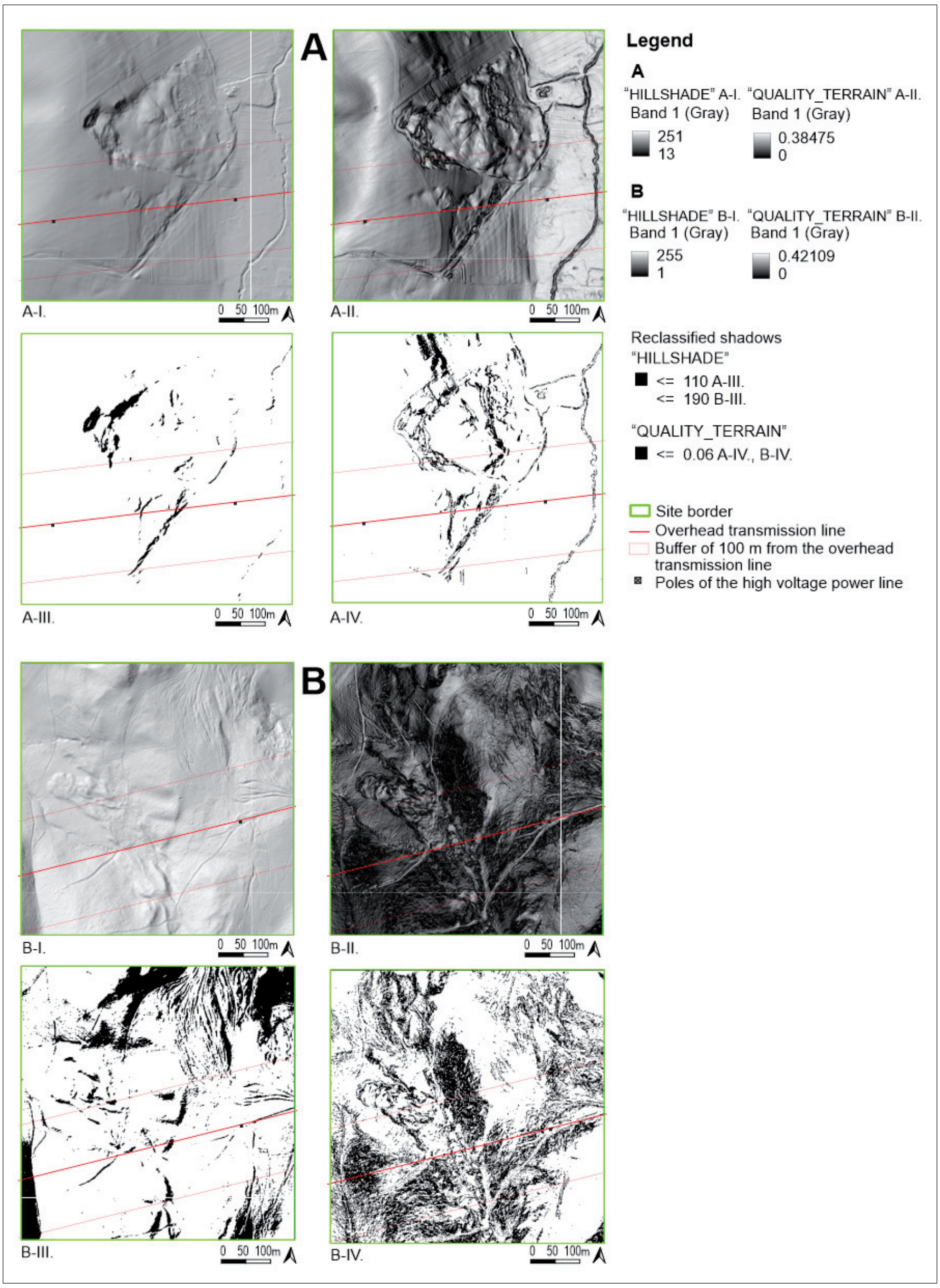

Fig. 5: Comparison between A-I., B-I. – the grayscale grid of "HILLSHADE" and A-II., B-II. – "QUALITY_TERRAIN". Visual comparison between A-III., B-III. – reclassified grayscale grid to binary grid of "HILLSHADE" and A-IV., B-IV. – reclassified grayscale grid to binary grid of "QUALITY_TERRAIN"
Source: VUJE a.s.: overhead transmission powerline, poles and protection zone, The Geodesy, Cartography and Cadastre Authority of the Slovak Republic: DMR5.0 (1 m) JTSK(JTSK03), State Geological Institute of Dionýz Štúr: slope failures, modified by the author; author's elaboration: "HILLSHADE", "QUALITY_TERRAIN"

Site/slope mean	A/9°	B/18°	A/9°	B/18°
Reclassified shadows of edges	[ha]		[%]	
"HILLSHADE": A ≤110 (A-III).; B≤190 (B-III.)*	0.52	0.13	2.08	0.52
"QUALITY_TERRAIN": A (A-IV)., B ≤ 0.06 (B-IV.)*	1.35	6.62	5.40	26.48
Total area	25	25	100.00	100.00
Wombling filter applied "HILLSHADE" to sum-up terrain edges and "QUALITY_TERRAIN"	[ha]		[%]	
"HILLSHADE" (red pixels)	1.96	1.77	7.84	7.08
"QUALITY_TERRAIN" (blue pixels)**	2.41	12.35	9.64	49.40
Total area	25	25	100.00	100.00

Tab. 2: Evaluation of terrain edges in the site area of 25 ha for sites A and B
*Notes: *Numbering of sites is adopted from Figure 5; **Figures 6 and 7*
Source: Authors' survey

Site/slope mean	A	B	A	B
Longitudinal terrain profile from edges	[m]		[%]	
"HILLSHADE"	52.00	13.48	17.00	7.88
"QUALITY_TERRAIN"	52.02	96.81	17.00	56.61
Total length	305.96	171	100.00	100.00
Transverse terrain profile from edges	[m]		[%]	
"HILLSHADE" (red pixels)	24.00	5.42	15.68	6.74
"QUALITY_TERRAIN" (blue pixels)	35.01	39.86	22.87	49.54
Total length	153.09	80.46	100.00	100.00

Tab. 3: Evaluation of terrain edges in the terrain profiles of the sites A and B
Source: Authors' survey

"HILLSHADE" also in forest (Appendix 3) and the similar contrast exhibited a gully in site C (Appendix 4). However, rugged terrain and steep slope (18°) made the QTerrain dark and contrast was not so visible in case of site B as we could observe in forest in C with smoother slope (9°). Site A had slope mean parameter the same as site C but a high contrast of slope steepness is visible between the terrain edges of slope failure and the surrounding slopes.

4.3 Evaluation of digitised slope failures a hillshade map enriched with QTerrain data

Slope failures digitised manually in grids of "HILLSHADE" and "QUALITY_TERRAIN" cover an area of 50 ha. In "HILLSHADE" 42 ha of slope failures were identified. Slope failures in an area of 8 ha were additionally detected using "QUALITY_TERRAIN" (Appendix 5). The floating-point based grid of "QUALITY_TERRAIN" highlighted and markedly distinguished these subtle landforms which "HILLSHADE" did

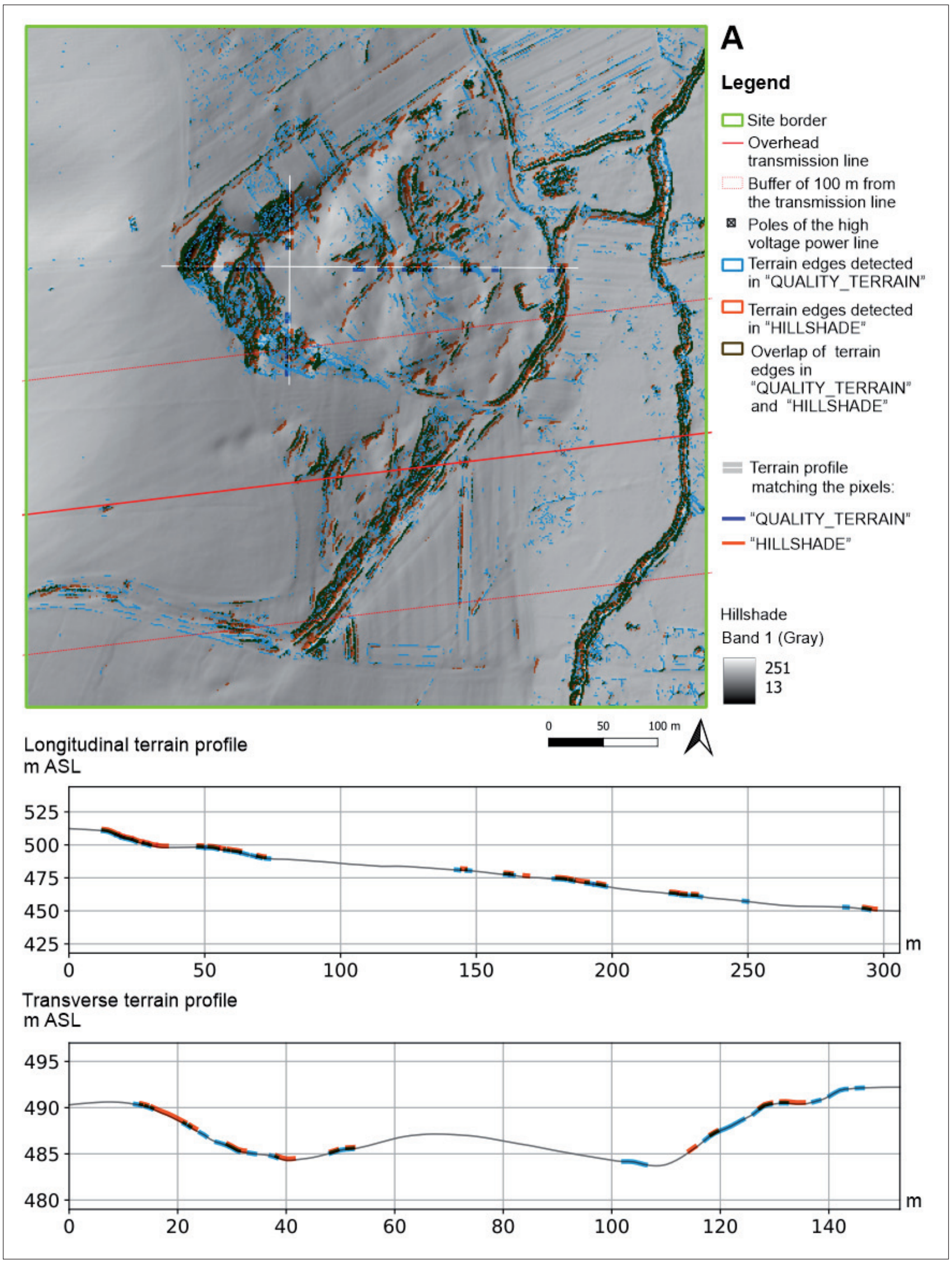

Fig. 6: Site A: Terrain edges evaluated in the grids of "HILLSHADE" and a product of the new method – "QUALITY_TERRAIN"
Source: VUJE a.s.: overhead transmission powerline, poles and protection zone, The Geodesy, Cartography and Cadastre Authority of the Slovak Republic: DMR5.0 (1 m) JTSK(JTSK03), State Geological Institute of Dionýz Štúr: slope failures, modified by the author; author's elaboration: "HILLSHADE", "QUALITY_TERRAIN"

not illustrate enough, these landforms – features typical for slope failures (explained in Fig. 1) (Appendices 6-1 and 6-2). "BIN_TERRAIN_EDGES" illustrated terrain edges in detail of black-coloured pixels.

In total, 13.5 ha of terrain edges was detected, 11.38 was observed inside the manually digitised polygons from "HILLSHADE" and 2.22 ha from polygons digitised in "QUALITY_TERRAIN". Slope failures clearly visible in "HILLSHADE" which do not require verification in the field were present on fifteen localities, namely: 4, 6, 7, 9, 10, 11, 12, 13, 14, 15, 17, 19, 20, 21, 22. Other, evidenced in "QUALITY_TERRAIN" were found on two localities, namely: 5QT, 6QT. Then, thirteen have required to be confirmed in the field. Appendices 6-1 and 6-2 demonstrates a pattern of terrain edges (in red) on which basis slope failures are easy to detect. Seven poles of the high voltage power line are located in the polygons of digitised slope failures (3, 6, 8, 9, 11, 13, 15) from which two sites needed to be confirmed in the field (3, 7).

5. Discussion

5.1 Benefits of the new method and challenges for future research

Subtle landforms of terrain edges are a subject of study for variety of landforms such as landslides (Chiba et al., 2008; Korzeniowska et al., 2018; Tarolli et al., 2020), gullies (Na et al., 2017; Yan et al., 2024), cultural terraces (Pijl et al., 2020), roads (Jiao et al., 2021; Slámová et al., 2023), linear structures (Satari & Kazimi, 2021) and many others.

Open-source QGIS tools have opened many possibilities for developing a variety of visualisation techniques and effective procedures are offered through GIS plugins or modules (Tzvetkov, 2018). One such licensed Python module – CSMapMaker – was developed specifically for landslide detection. It's released under the GNU Public License (GPL) Version 2 and authorised by Kosuke Asahi (QGIS Python Plugins

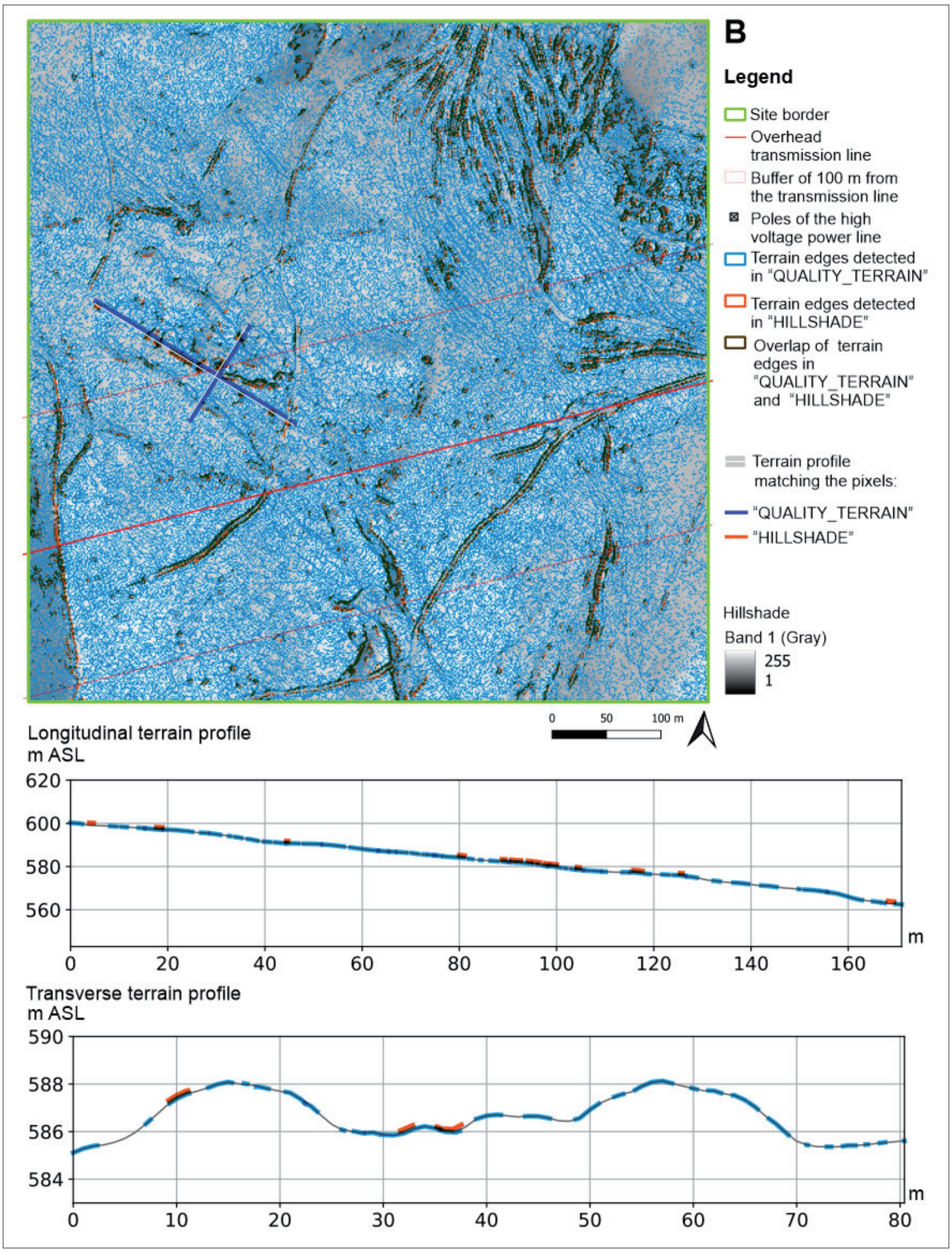

Fig. 7: Site B: Terrain edges evaluated in the grids "HILLSHADE" and a product of the new method – "QUALITY_TERRAIN"
Source: VUJE a.s.: overhead transmission powerline, poles and protection zone, The Geodesy, Cartography and Cadastre Authority of the Slovak Republic: DMR5.0 (1 m) JTSK(JTSK03), State Geological Institute of Dionýz Štúr: slope failures, modified by the author; author's elaboration: "HILLSHADE", "QUALITY_TERRAIN"

Repository, 2019). This module enables the identification of landslides based on a red relief image map (RRIM) and colour contrast formed by terrain edges visualised by superimposing different derivatives of a digital terrain model (Chiba et al., 2008; Chiba & Hasi, 2016). A first comparison between RRIM outputs and landslides detected using a binary raster of terrain edges introduced Chudý et al. (2019).

RRIM is a set of superimposed grid maps, not a single raster. The outputs of the newly developed method are: the binary grid of BinTerrain ("BIN_TERRAIN_EDGES") (Fig. 3), the grey scaled grid of QTerrain ("QUALITY_TERRAIN") and its red-grey coloured modification "RED_GRAY_CONTRAST" (Fig. 4). The advantage of interpreting terrain edges in a single grid map over RRIM lies in the potential for further processing using raster-based operations.

The advantages of the pixel-based method lie in the number of GIS tools readily available and usable for operations on the pixel raster intended for digital terrain models, even for the common user. Logical and arithmetic operations, classification, overlay, and fusion of images derived from detailed digital models can yield derivatives applicable across various scientific disciplines, such as archaeology (Kokalj & Somrak, 2019; Štular et al., 2012), geomorphology for slope deformation indications (Pirotti & Tarolli, 2010; Guzzeti et al., 2012; Peternel et al., 2017; Chudý et al., 2019; Jagodnik et al., 2020), applied ecology (Leempoel et al., 2015), or environmental history (Lieskovský et al., 2022). Combining land cover structures with quasi-3D relief raster files, such as overlapping slope, topographic openness, and multidirectional hillshade, proves valuable in visualising the topographic pattern of slope failures, even in the case of older landslides (Lee et al., 2017).

Easy transfer between raster and vector forms enables simple measurements of slope movements. Measuring is important to monitor slope failure activity (Lucieer et al., 2014) and it can be achieved using multi-temporal LiDAR digital terrain models (Anders et al., 2013). Binary interpretation of terrain edges pixels in the grid makes it possible to identify, delimit and finally evaluate their area or length as we documented on the study sites. Terrain edges of slope failures appeared more frequently and on more extensive area in "QUALITY_TERRAIN" as it was in "HILLSHADE" grid (Tabs. 2 and 3; Figs. 5, 6 and 7; Appendix 2). The visual prominence of the outputs of the newly developed method supports also spatial visualisations of "HILLSHADE" and "QUALITY_TERRAIN" overlapped with ortho-photomosaic. QTerrain exhibited markedly higher contrast in overlaid layers with agricultural and forest landscape against hillshade map (Appendices 3 and 4).

Manual digitising of subtle landforms in an extensive area would be time consuming and inefficient. The hillshade map does not provide interpretation of terrain edges in such a detail as QTerrain as shown at sites 1QT–8QT (Appendices 6-1 and 6-2). A user may unintentionally overlook and omit landslides with indistinct terrain edges which do not cast sufficient shadows in the hillshade map. Jaboyedoff et al. (2018) found that not all slope failures can be identified in digital derivatives of DTM. We found slightly less than half (13 sites) of their total number that would need to be confirmed in the field survey.

Regarding the extensive area along the OHL construction, we are aware of the spatial discontinuity of the investigated slope failures. The reason for the selection was the project objective to identify slope failures in this area using an innovative method. An actual challenge is to perform field measurements of terrain edges in the transects of site A and B using professional GNSS (Chudý et al., 2018a, b, Chudý et al., 2019) and adopt a method by Du et al. (2023) to evaluate correspondence or divergence of data digitally computed in the transects with data measured in the field. Based on the results we would be able to identify: correctly computed terrain edges, false positives (non-existent edges) and false negatives (missing edges). Further, this comparison would suggest which output of the new method BinTerrain or QTerrain could be more suitable to generate a pattern of landslide features. Geometric pattern consisting of geometric shapes (Fig. 4 and Appendices 6-1 and 6-2) derived from binary interpretation of terrain edges would be employed to automate detection and inventorying landslides on a landscape scale. Pixel-based terrain variables thresholds allow easy and flexible adapt the same diagnostic terrain variables as predictive inputs to machine learning models (Brecheisen & Richter, 2021; Masruroh et al., 2023).

5.2 Applicability of the method

A prospective model for landslide mapping and monitoring is predicated upon the utilisation of multiscale and multitemporal spatially referenced data from a diverse array of sources (Hou et al., 2017). A geomorphometric analysis of slope failures and their selected features derived from disparate data sources on different scales enables the identification and categorisation of multiscale components of slope failures (Mora et al., 2018). The classification of landforms is inherently scale-sensitive as, for instance, the Topographic Position Index demonstrates (Giano et al., 2020). DTMs of different resolutions contain different topographic information, resulting in variations in the spatial distribution of terrain parameters on different scales, which has a significant impact on the spatial distribution of calculated parameters such as slope and water flow distribution (Thomas et al., 2017). The new method showed its robustness when it was applied on three different resolutions of DTMs and multiscale application was demonstrated on site C (Appendix 7). We compared "HILLSHADE" and "QUALITY_TERRAIN" at three resolutions of DTM: 10 m, 1 m and 0.15 m per pixel. The most obvious difference was in DMR3.5 between "QUALITY_TERRAIN" and "HILLSHADE" in which the shape of the gully was difficult to recognise. DMR5.0 distinctly depicted slope failure features such as scarps, tension cracks, and transverse ridges, among others. While DMR3.5 lacked the resolution necessary to detect subtle landforms, on the other side, general shape of a gully was markedly visible. Thus, lower resolution DTMs could be helpful to indicate erosion objects or sliding slopes over extensive areas, on a landscape scale. In contrast to lower resolutions, extra dense LiDAR with the average point density of 254 PPSM per ground was used. It demonstrated the potential to complement the DMR5.0 data, visualising subtle landforms in intrinsic detail even in forests with dense tree canopy and shrub stage, rugged terrain, deep valleys, ravines or gullies with steep slopes which make obstacles for penetration of laser.

Forest has many limitations for aerial LiDAR or photogrammetry (Van Den Eeckhaut et al., 2007). LiDAR appears to be more suitable than photogrammetry for mapping subtle landforms due to its ability to penetrate dense canopies, whereas photogrammetry often leaves many data gaps (Chudý et al., 2018a,b). More detailed data can be collected using hyperspectral sensors. These can provide exceptionally detailed spectral surface reflectance data, but their processing, especially from airborne cameras, requires complex corrections, making them difficult to use for terrain mapping (Jakob et al., 2017). The fusion of extra dense LiDAR with selected indices from hyperspectral data could help to explore relationships between vegetation and subtle landforms (Demarchi et al., 2020). However, high-resolution digital models are beneficial for extracting target topography only when the model accurately represents well-defined terrain morphology (Sofia et al., 2010).

The presence of slope failures on different slope grades (DMR5.0) in the area along the OHL construction was indicated according to terrain edges calculated from "BIN_TERRAIN_

EDGES". More than half of their total amount inside the digitised polygons of slope failures was found on slopes steeper than 15° (7.13 ha); 4.45 ha was within the interval from 15° to 25° what aligns with findings from other authors (Zęzere, 2002; Frattini et al., 2004) and 2.68 ha was found above 25° (Appendix 5). Initially, we assumed that the usability of BinTerrain or QTerrain on slopes above 25° might be limited due to the low contrast between the subtle landforms of slope failures and other landforms in their vicinity. Terrain edges of QTerrain casted more shadows in case of site B with slope mean 18° against site A with slope mean 9° In site B, QTerrain exhibited circa seven times higher presence of shadows against the hillshade map (Tabs. 2 and 3, Figs. 5, 6 and 7).

6. Conclusions

While contactless technologies have a wide range of applications, their limitations lie in data quality, processing time and financial investment. The most efficient dataset in the research was considered to be DMR5.0. Results demonstrated that binary and grey shaded grid derivatives had sufficient resolution to visualise even subtle landforms which may indicate initial phases of the slope movement.

The main benefit of the proposed method is seen in the interpretation of the pattern of terrain edges which is typical for slope failures. Discrete interpretation BinTerrain – "BIN_TERRAIN_EDGES" exactly shows terrain edges with a certain resolution given by the DTM. Binary patterns of different types of slope failures could be used as training datasets for machine learning algorithms in future research. In comparison, manually digitised polygons are subjectively vectorised and borders suffer for lack of details. Application of these polygons of slope failures as training datasets based on grid in machine learning is questionable. Here, exact binary interpretation of terrain edges would bring more accurate results.

The main advantage of QTerrain's floating-point grid is that it enhances the contrast of terrain edges, making them easy to recognise even in large areas on a landscape scale. Coloured interpretation of QTerrain is comparable with known RRIM raster that is the algorithm used to detect terrain edges of failed slopes. Applicability of the method across different resolutions of DTMs makes it flexible to use on different geographic scales which are relevant for mapping of terrain edges.

Terrain edges casted more shadows in QTerrain than in the hillshade map and the most visible difference was on steeper slopes (site B, 18°) while moderate slopes (A, 9°) have not exhibited so contrasting presence of shadow casted by terrain edges between the hillshade map and QTerrain. Moreover, as slope failures predominantly occur on slopes above 15°, these slopes are often covered with shrubs or forest. Floating-point base grid of QTerrain allows clear and sharp visualisation of terrain. Identification of subtle terrain edges in visualisations combining terrain and real land cover – orthophotomosaic is easier than in the hillshade map overlapped with land cover.

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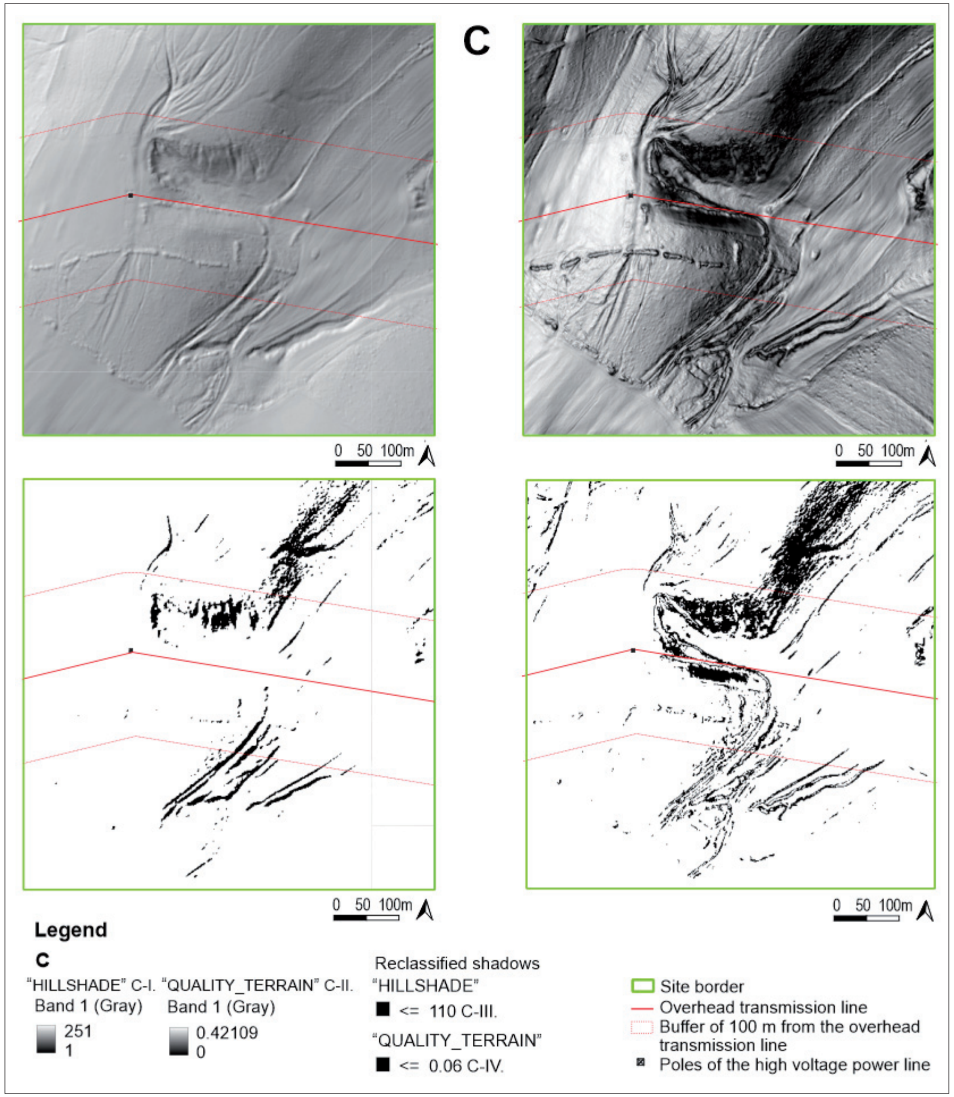
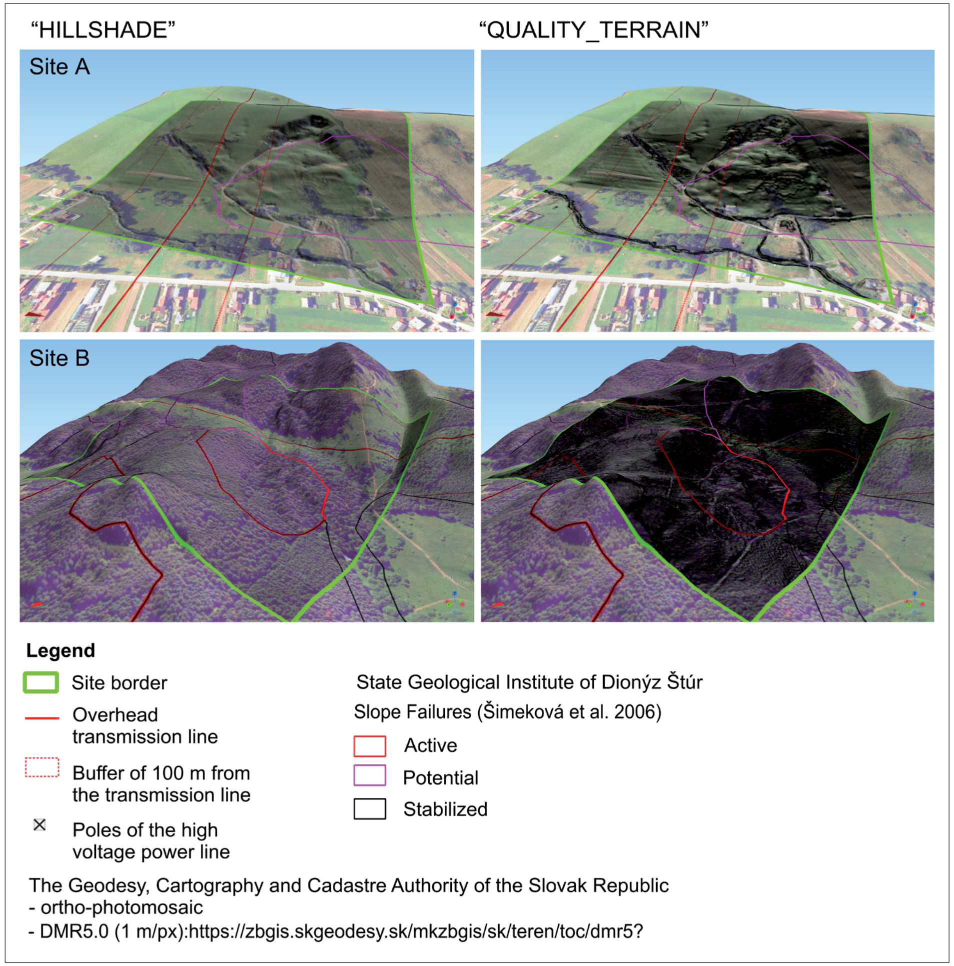
Appendices

Appendix 1: The protection buffer zone (100 m) of the overhead transmission powerline
Photos: M. Slámová (2023)

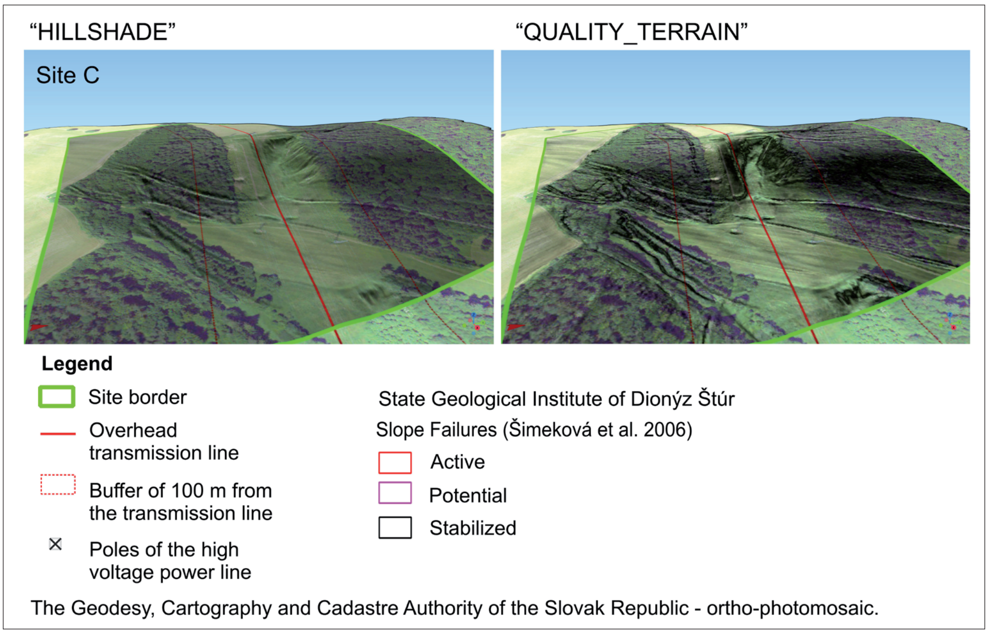
Appendix 2: Visual comparison between C-I. – the grayscale grid of "HILLSHADE" and C-II. – "QUALITY_TERRAIN", visual comparison between C-III. – reclassified grayscale grid to binary grid of "HILLSHADE" and C-IV. – reclassified grayscale grid to binary grid of "QUALITY_TERRAIN"
Source: VUJE a.s.: overhead transmission powerline, poles and protection zone, The Geodesy, Cartography and Cadastre Authority of the Slovak Republic: DMR5.0 (1 m) JTSK(JTSK03), modified by the author



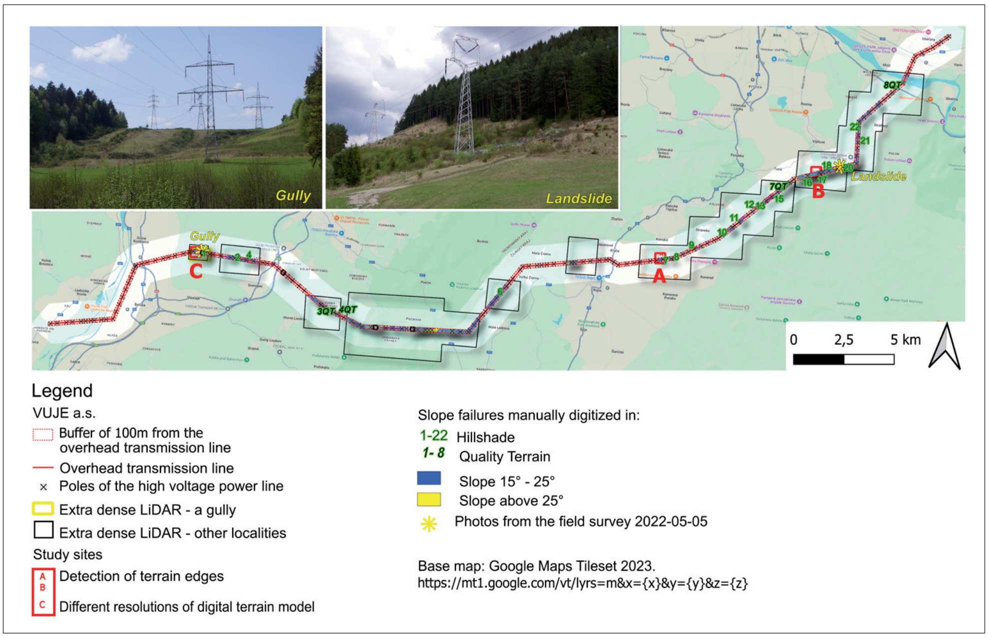
Appendix 3: Sites A, B – Spatial visualisations created from DMR5.0 with "HILLSHADE" and "QUALITY_TERRAIN" overlapped with ortho-photomosaic
Source: VUJE a.s.: overhead transmission powerline, poles and protection zone, The Geodesy, Cartography and Cadastre Authority of the Slovak Republic: DMR5.0 (1 m) JTSK(JTSK03) and ortho-photomosaic, State Geological Institute of Dionýz Štúr: slope failures, modified by the author



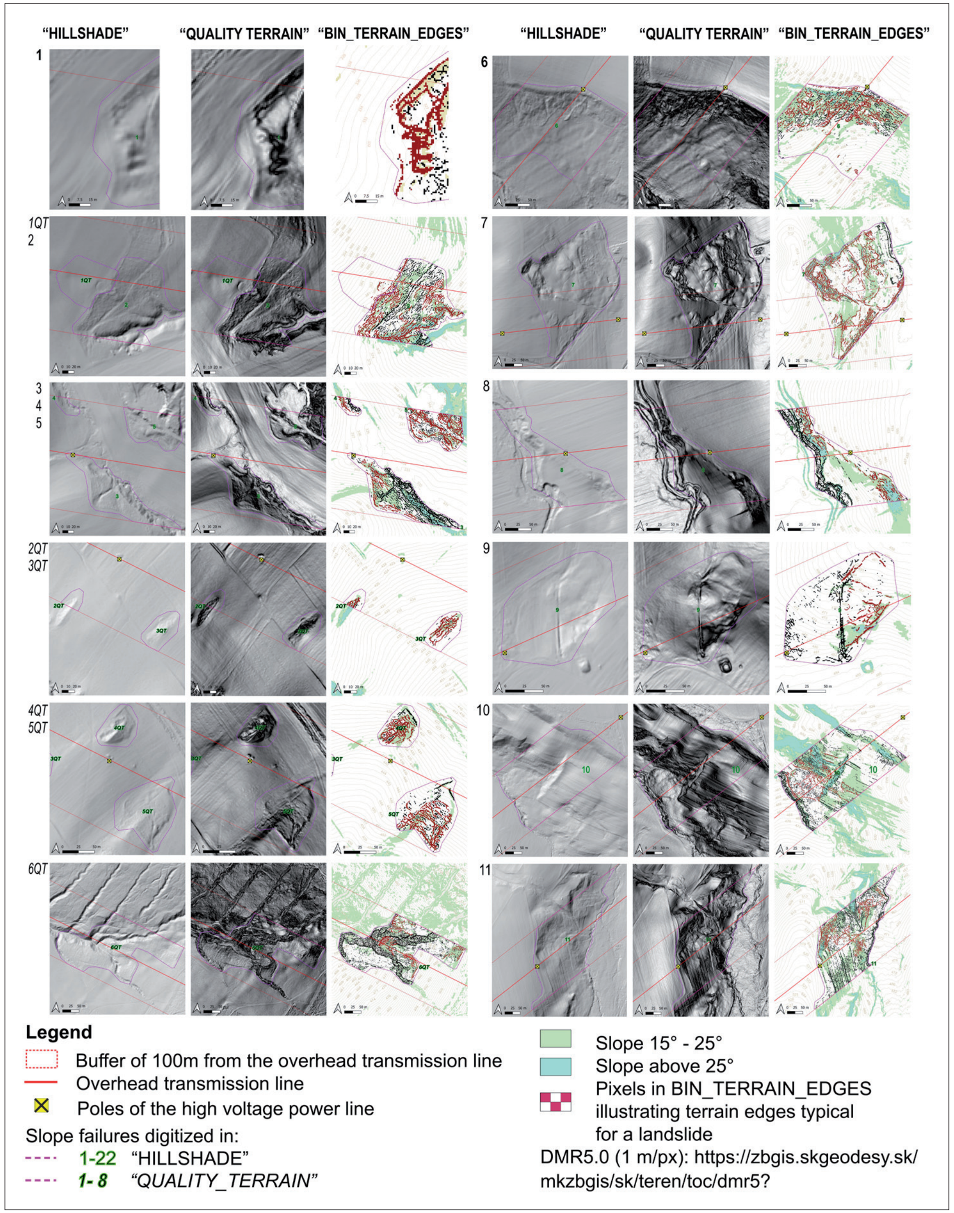
Appendix 4: Site C – Spatial visualisations created from DMR5.0 with "HILLSHADE" and "QUALITY_TERRAIN" overlapped with ortho-photomosaic
Source: VUJE a.s.: overhead transmission powerline, poles and protection zone, The Geodesy, Cartography and Cadastre Authority of the Slovak Republic: DMR5.0 (1 m) JTSK(JTSK03) and ortho-photomosaic, State Geological Institute of Dionýz Štúr: slope failures, modified by the author

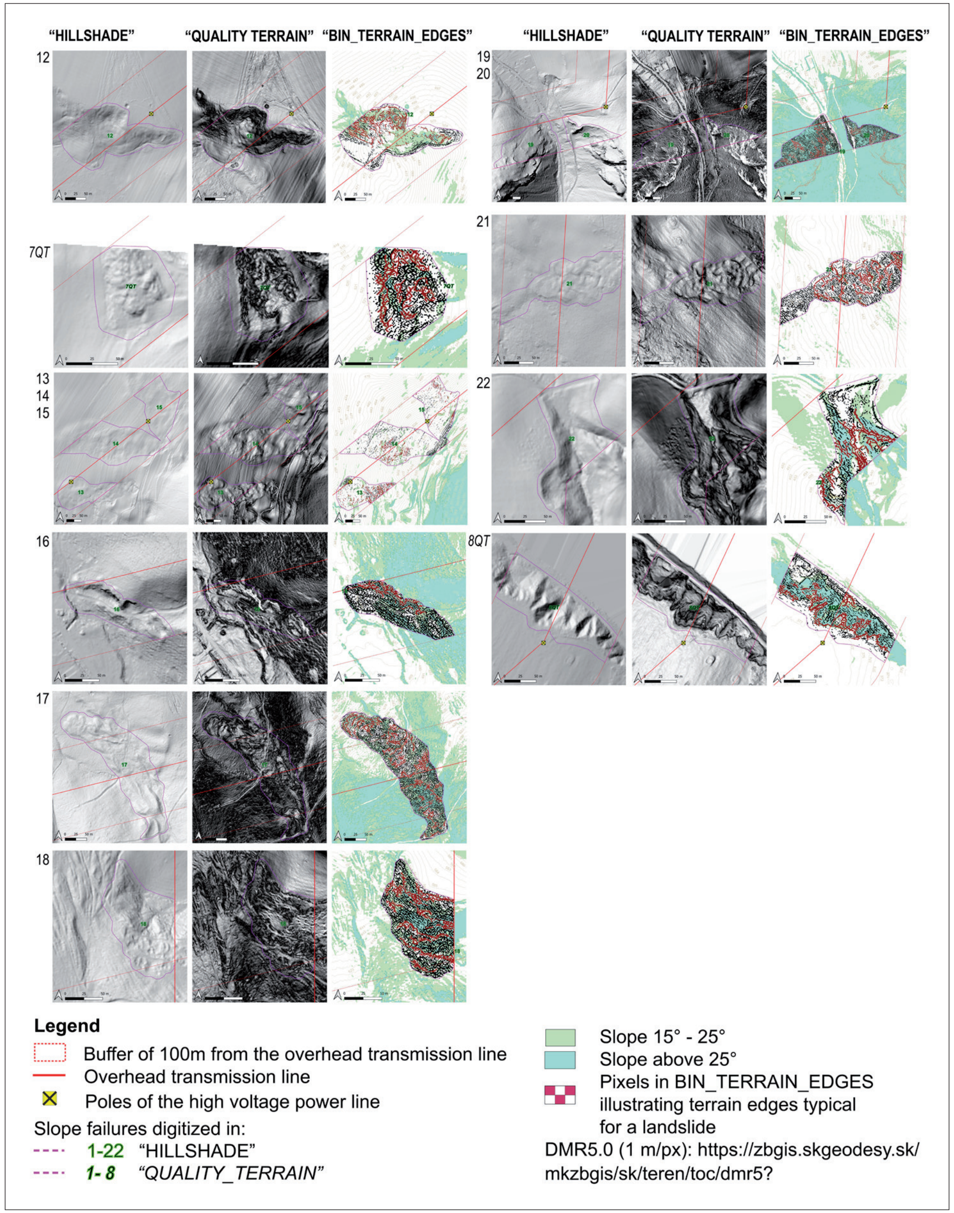


Appendix 5: Slope failures digitised on the basis of "HILLSHADE" and "QUALITY_TERRAIN" and their location on slopes of different categories
Source: VUJE a.s.: overhead transmission powerline, poles and protection zone, Google Maps Tileset, modified by the author; author's elaboration: "HILLSHADE", "QUALITY_TERRAIN" and slope; photos: M. Slámová (2023)

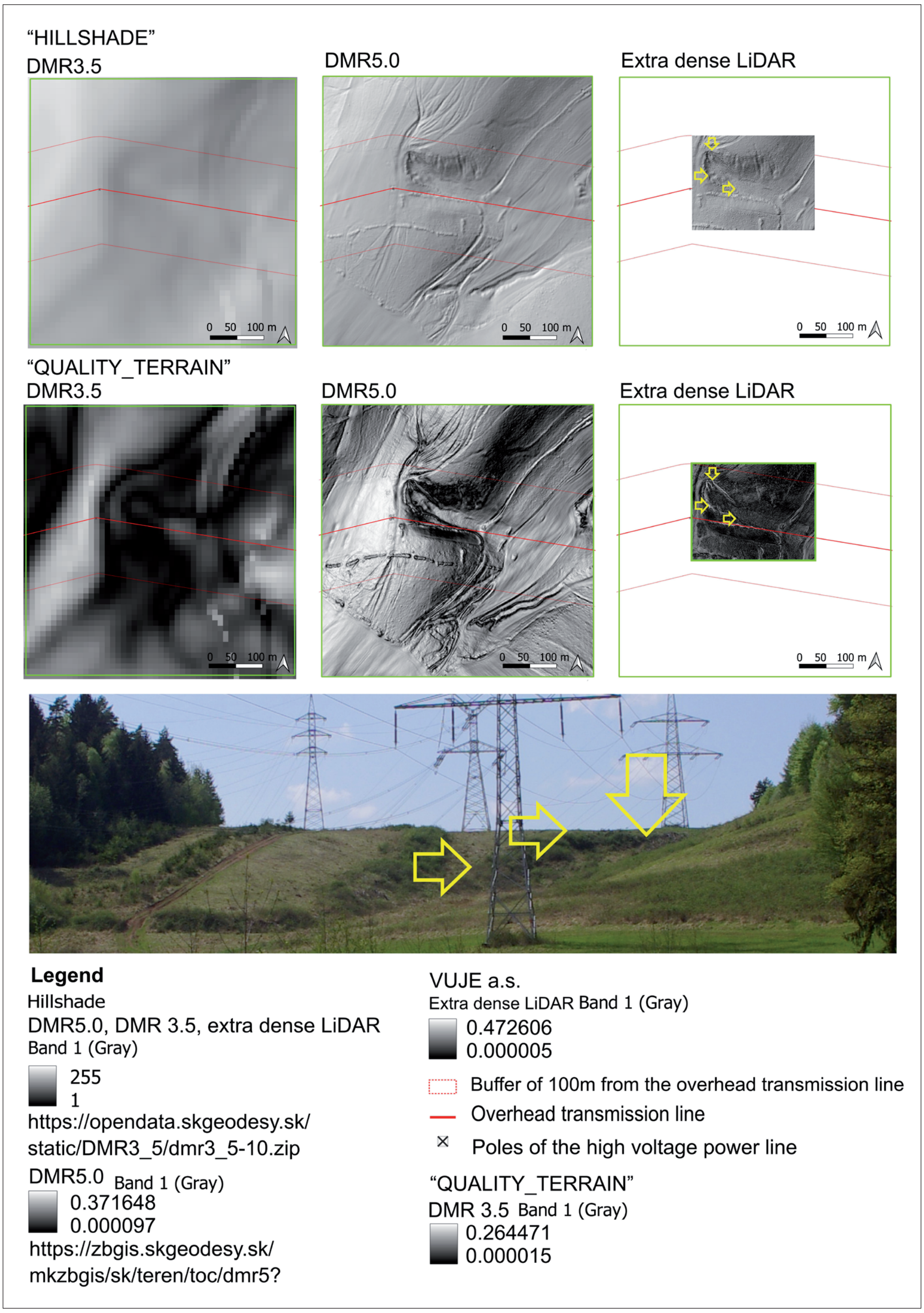


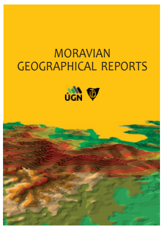
Appendicces 6-1 (left) and 6-2 (right): Interpretation of digitised slope failures in "HILLSHADE", "QUALITY_TERRAIN" and "BIN_TERRAIN_EDGES" on different slopes. Red coloured is a pattern of slope matching shapes of scarps, cracks and transversal ridges (defined in methodology)
Source: VUJE a.s.: overhead transmission powerline, poles and protection zone, The Geodesy, Cartography and Cadastre Authority of the Slovak Republic: DMR5.0 (1 m) JTSK(JTSK03), modified by the author; author's elaboration: "HILLSHADE", "QUALITY_TERRAIN" and slope





Appendix 7: Site C: Application of the new method to different resolutions of digital terrain models to identify terrain edges on slopes in "QUALITY_TERRAIN"
Source: VUJE a.s.: overhead transmission powerline, poles, protection zone and extra dense LiDAR, The Geodesy, Cartography and Cadastre Authority of the Slovak Republic: DMR5.0 (1 m) JTSK(JTSK03) and DMR3.5 modified by the author; author's elaboration: "HILLSHADE", "QUALITY_TERRAIN"; photo: M. Slámová (2023)





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Effects of policy changes in the last 80 years on LU/LC and ecosystem services: A case study of the Odra River floodplain (Czech Republic)

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Abstract

Riverscapes are degraded and threatened by human activities. We investigated the spatiotemporal dynamics and trends of land use/land cover (LU/LC) and ecosystem services (ES) in the floodplain of the Odra River in the Czech Republic over the last 80 years. Our focus was on: (i) the effects of changing political regimes and environmental policies on changes in LU/LC and ES (agricultural potential, natural flooding, and water provision and quality), and (ii) the effects of the establishment of a protected landscape area (Poodří PLA) on ES over the last 30 years. To assess LU/LC changes, we performed vectorization and categorization using aerial images. For ES assessment, we analyzed the spatial distribution of LU/LC and other characteristics in our study area. Potential agricultural ES showed a decreasing trend, similar to neighboring countries, while natural flood mitigation and water ES increased due to the decline in arable land. Policy assessments revealed significant changes in LU/LC. The Poodří PLA significantly enhanced ES by preserving the riverscape. This research demonstrates the under-researched long-term monitoring of ES, including before and after evaluation of the PLA, and highlights the importance of practical nature conservation for the riverscape ecosystem benefits to human society.

Keywords: Land Use/Land Cover, Ecosystem Services, Trend, Protected Landscape Area, Environmental Policy

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1. Introduction

Rivers and their floodplains are an essential part of the landscape (Tockner & Stanford, 2002; Wohl, 2021). These areas are perceived as multifunctional landscapes (Funk et al., 2019; Jakubínský et al., 2021; Schindler et al., 2014), where the functions of the river landscape depend on the river pattern (and its various characteristics, e.g., width and sinuosity) and human interventions through policies that change land use/land cover (LU/LC) and river channel alterations (Thorp et al., 2010). Ecosystem services can be used to assess all these changes.

Costanza et al. (2017) defined ecosystem services (ES) as "ecological characteristics, functions, or processes that directly or indirectly contribute to human well-being, that is, the benefits that people derive from functioning ecosystems." ES are divided into four main categories: provisioning services, regulating services, cultural services and supporting services (Haines-Young & Potschin, 2018; Keele et al., 2019). The variety and quality of ES depend on environmental conditions and ecosystem functions. All types of ES categories (provisioning, regulation, cultural services and supporting) are represented in a river landscape. Firstly, supporting services represent the natural foundation for other ES. Provisioning services include fisheries (aquaculture), agriculture, water (for nondrinking purposes), and raw (biotic) materials. Regulation services include flood protection, water purification, carbon storage, and erosion control, among others. Cultural services include recreation, spirituality, and symbolic appreciation (Grizzetti et al., 2015; Haines-Young & Potschin, 2018).

According to Opperman et al. (2010), rivers and their floodplains are among the most productive ecosystems on Earth. In a literature review, Hanna et al. (2018) identified more than 33 services from 89 relevant studies on the ES of riverscapes. Floodplains are often flat, accessible and fertile areas (Jakubínský et al., 2021); due to these characteristics, these lands have been settled by societies since prehistoric times (Munoz et al., 2014; Petřík et al., 2019). Humans have gradually altered the dynamics of floodplains, with the intensification of agriculture in the 19th century accelerating these changes (Hooftman & Bullock, 2012). In Europe, it is estimated that 70–90% of floodplains are in a degraded eco-hydromorphological state (European Environment Agency, 2018); the situation is similar in North America (Tockner & Stanford, 2002). Floodplain degradation is most evident in urban areas (Jakubínský et al., 2021); river adjustments (changing sinuosity, embankments, or fragmentation by horizontal barriers) have reduced ecosystem functions and ES (Large & Gilvear, 2015). Previous research, however, rarely studied ES of riverscape in large longitudinal scale or assess ES from historical data of aerial images. In our study, we focused on the part of the lowland with continuous floodplain of the river corridor of the Odra River in the Czech Republic (a corridor between the cities of Odry and Ostrava) to demonstrate:

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1. How changing political regimes and policies have affected LU/LC, as reflected in the provision of ES at two different spatial scales (the scale of the whole river corridor and individual river segments) over the last 80 years?
2. How have ES, namely agricultural potential, natural flooding, and water (water quality and supply) changed?
3. How the establishment of a landscape protected area under the Ramsar convention, based on changed environmental policy, has affected ecosystem services over the last 30 years?

River corridors provide a wide range of ES, encompassing provisioning services such as biomass production, regulating services like carbon capture and habitat provision or cultural services including recreation and heritage (Jakubínský et al., 2021). The selection of ES was made based on their representative characteristics, which reflect the characteristics of the broader territory. Emphasis was placed on the identification of potential agricultural ES, which are crucial for understanding land-use dynamics and productivity, as well as river-related services, which play a significant role in hydrological processes, biodiversity conservation, and the provision of ecosystem functions associated with water bodies. We provide a unique insight into the river landscape of Central Europe, which, in contrast to less detailed scales, shows the tangible results of policy changes. This study provides a compelling case for advocating the establishment and protection of protected areas, and for conducting assessments that sensitively reflect the policy changes of the last 80 years in Central Europe. We aim to understand how political shifts and policy changes have modified LU/LC and ES and to contribute to a comprehensive understanding of landscape evolution.

2. Theoretical and institutional background

In assessing the transformation of LU/LC, the chosen scale is an integral part of the assessment process. Study authors typically use a less detailed scale, such as a planetary scale (Costanza et al., 2017) that focuses on the evolution of the ES and estimates its value, or a national scale (e.g., Bičík et al., 2015; Aziz, 2021; Schirpke et al., 2023). The former approach is less commonly used (Burkhard et al., 2009; Requena-Mullor et al., 2018), and only a limited number of studies have been conducted at a more detailed scale. Examples of such studies include Peterson et al. (2003), Keele et al. (2019), and Stammel et al. (2021). Nevertheless, research conducted at this level of detail may be more sensitive to the actual consequences of policy changes and LU/LC. At the national or regional scale, only extreme manifestations can be observed (Schirpke et al., 2023).

Another key element in assessing changes in LU/LC is the analysis of the drivers of these changes. The provision of ES can be affected by changes in LU/LC as consequences of societal dynamics (Aziz, 2021; Hasan et al., 2020; Schirpke et al., 2023). In addition, disasters or climate change can act as a catalyst for change. In Central Europe, society has been an important driver of LU/LC change over the last 80 years (Aziz, 2021; Bičík et al., 2015; Schirpke et al., 2023). There were several political and social changes in Europe during the 19th and 20th centuries that affected LU/LC. These included the Industrial Revolution, World War I and the fall of the Austro-Hungarian monarchy, the establishment of new republics, the Great Depression, World War II, the rise and fall of communism, and the establishment of democratic regimes in the post-Soviet republics. These events affected the landscape in various forms and intensity. While some changes manifested in form reformation of local policies, others changed it dramatically, such as the nationalization of the lands (Grešlová Kušková, 2013). In the Czech Republic, this resulted in the creation of large agricultural plots, while in neighboring Austria the land remained much smaller and more fragmented (Schirpke et al., 2023). The consequences of land nationalization became evident over time through various adverse effects, including diminished water retention capacities of the land and watercourse regulations. Additionally, the intensive agricultural practices involved the extensive use of chemical fertilizers, resulting in negative impacts on biodiversity and soil quality (Kupková et al., 2021; Schirpke et al., 2023).

The identification of these issues was the initial step towards mitigating and potentially reversing the damage. The alteration of the political regime and other sociopolitical structures were major steps that led to the establishment of the Poodří protected landscape area (PLA). However, this was not an uncomplicated process, as the first proposals for its establishment appeared as early as the 1980s (Jarošek, 2021). The advantage of our research is that we observe the situation before and after the establishment. Kaiser et al. (2021) criticize that most of the studies evaluating river restoration and its impact on the ES in her case struggle with drawing conclusions based only on 'after' revitalization data. There is a complete lack of data before the restoration. Overall, it is important to protect and improve the condition of the river. As an improvement can be small or large river restoration or complex adjustments (Large & Gilvear, 2015). Stammel et al. (2021) evaluated ES of river corridors in the question of construction of flood control measures. Keele et al. (2019) evaluated pairs of rivers, one with and one without nature conservation designations. Both showed that the river landscape with more natural river provides better ecosystem services. So, it is important to support conservation. Several laws and directives have been established to prevent the degradation of river corridors, such as the European Water Framework Directive, the Habitats and Birds Directives, EU Biodiversity Strategy for 2030, Natura 2000 and the Ramsar Convention. In addition, there is much more to be done on the issue of river landscape protection and conservation.

3. Methodology

The methodology consists of several steps, starting with a description of the study area and its environmental and socio-economic characteristics. This is followed by a description of LU/LC assessment. The following chapter describes the assessment of each ES. The methodological framework (Fig. 1) is based on the availability of data and the spatial coverage of the study area (blue color). The results of the assessment of LU/LC and ES (green color) are placed in the context of political and social changes (purple color) to understand the trends and overall results (orange color) of the Odra River floodplain.

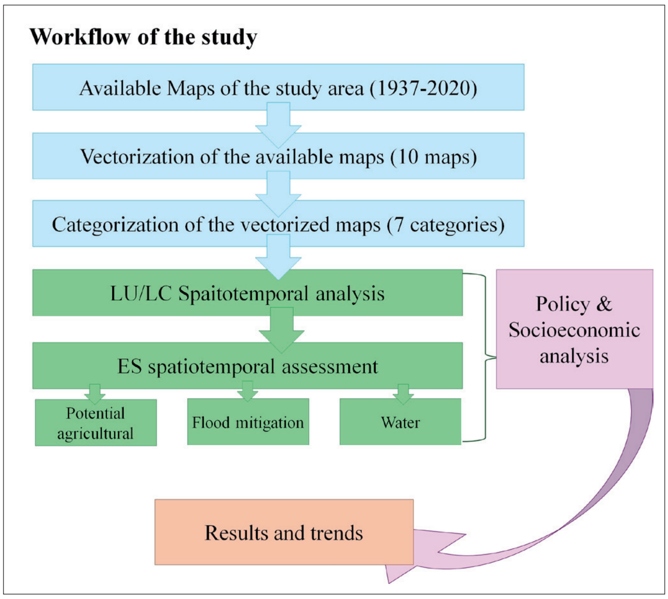

Fig. 1: Workflow of the research
Source: Authors' conceptualization

3.1 Study area

3.1.1 Geographical characterization of the study area

The study area is located in Central Europe, in the north-eastern part of the Czech Republic (Fig. 2). The study area is a river floodplain flanked by two urban areas: the smaller town of Odry and the city of Ostrava, which was one of the most developed regions of the Austro-Hungarian Empire, characterized by large factories and extensive coal mining areas. Land use and land cover changed rapidly over the years as the city expanded due to urbanization, agricultural and industrial demands (Bičík et al., 2015). In the midst of urban growth, woodlands, grasslands, and watercourses were preserved, creating a unique natural landscape between these urban centers. The water bodies are artificial ponds with normal (fish farming) and special management (natural ecosystem protection combined with fish farming) (Bartoš, 2011). The central part of the study area is part of the Poodří PLA, which was established in 1991 and includes 10 Small Spatially Protected Areas. It is part of the Ramsar Convention and Natura 2000 network. A free meandering river is the uniqueness of the European scale. Man-made and natural water bodies create biodiversity hotspots for fauna and flora.

It is a nesting place for more than 400 bird species, including the white-tailed eagle (*Haliaeetus albicilla*) (Bartoš, 2011). Arable land, orchards, and small urban areas can be found throughout the study area. The dominant element in the whole area is the Odra River. The Odra River is a major European river that rises in Oderské Vrchy (Czech Republic) and flows northeast through the Moravská Brána plain to the border with Poland. The river is 854 km long: 113 km flows in the Czech Republic and 742 km in Poland. The total area of the river basin is 118,861 km^2 (Brosch, 2005).

The Odra River originates as a torrential channel at an altitude of 632 m a. s. l. and downstream it develops into an extensive floodplain with typical phenomena such as oxbow lakes and abandoned channels, which are the target features of the Poodří Protected Landscape Area. Due to the dominant influence of the right tributaries (gravel-bed rivers), the sediment delivered to the Odra River channel mainly consists of gravels. Therefore, gravel bar formations are common in the Odra River and its tributaries (Eremiášová & Skokanová, 2014; Holušová & Galia, 2020). The Odra River is mainly regulated (managed) by straightening, embankment or weir construction and nearby cities such as Ostrava or Odry. In the 1960s, intensive regulations were implemented in Ostrava due to subsidence problems in the undermined area (Brosch, 2005).

3.1.2 Characterization of political and socio-economic changes in the study area

The beginning of our study period was in 1937, characterized by a market-oriented and democratic economy with a strong focus on agriculture and land development (industrialization and urbanization (Grešlová Kušková, 2013)). This development was interrupted from 1938 to 1948 by the German occupation, the Second World War and the post-war period (Kupková et al., 2021). From 1948 to 1989, the political regime was communist, characterized by totalitarian rule and a centrally planned economy. The Communists carried out the nationalization and collectivization of agriculture and industry, which destroyed private property (Bičík et al., 2001; Kupková et al., 2021). The effects of LU/LC were noticeable, before 1948 the land was characterized by small farms with fields, after 1948 small farms were replaced by a large agricultural cooperatives and fields were transformed into a large productive block (Grešlová Kušková, 2013).

In the 1970s, the first attempts were made to protect and preserve the landscape. In our study area, two small, protected areas were established: Polanský Les (1975) and Polanská Niva (1985). However, natural resources were exploited, rather than protected (Bičík et al., 2001). In 1989, the communist regime collapsed, a market-oriented and democratic economy was re-established, and the legal rights of landowners were respected

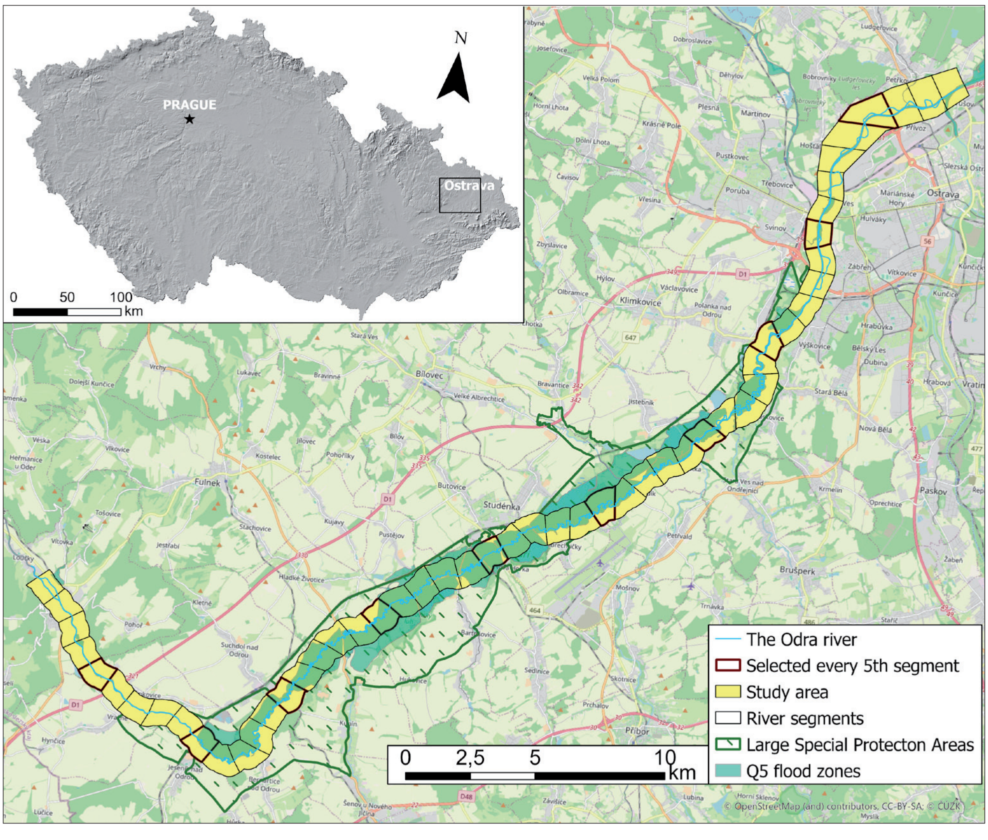

Fig. 2: Map of the studied river (Map inspired by Stammel, 2020)
Source: Authors' conceptualization based on the Base map of the Czech Republic and DEM map of the Czech Republic provided by State Administration of Land Surveying and Cadastre (Czech Republic)

(Bičík et al., 2001). Land protection and conservation became an important issue, and the Ministry of Environment was established in 1989. The Poodří Protected Landscape Area was established in the study area in 1991 (Jarošek, 2021). In 2004, Czech Republic became a member of the European Union, and the corresponding legislation and policies were implemented. The year 2020 was considered as the end of the assessment period, without any significant political or social changes. The following timeline (Fig. 3) illustrates the implementation of each policy and significant historical milestones.

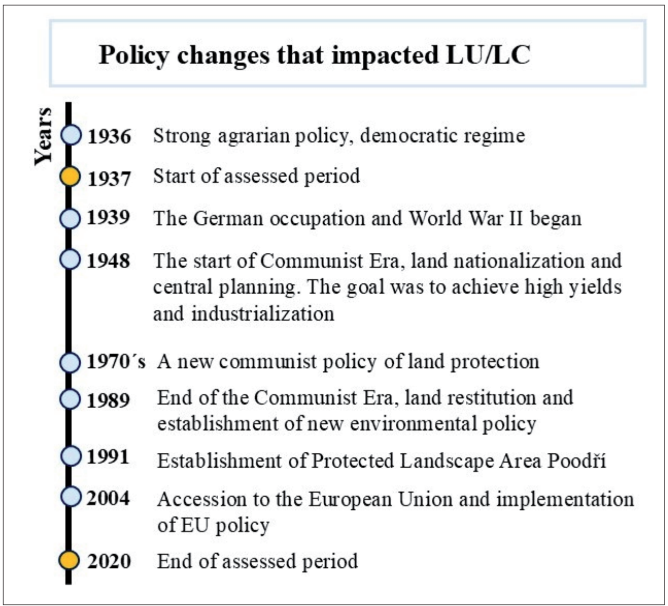

Fig. 3: A timeline of policy changes that impacted LU/LC
Source: Authors' conceptualization

3.2 LU/LC analysis and assessment

In order to achieve both objectives, it was necessary to carry out vectorization and LU/LC categorization of the study area. The vectorization was based on aerial images from 1937, 1949, 1955, 1966, 1973, and 1990 provided by the Military Geographical and Hydrometeorological Office in Dobruška (Czech Republic) and orthophotos from 2003, 2012, and 2020 provided by the State Administration of Land Surveying and Cadastre (Czech Republic). Historical aerial images were georeferenced and combined into raster mosaics using Geomatica 2014 software (PCI Geomatics). The root mean square error (RMS) of the georeferencing varied between 0.02 to 1.5. The highest RMS value was caused by the lower quality of the older aerial images (i.e., 1937). The 1937, 1949, 1966, and 1973 datasets do not fully cover the study area. We defined this map as uncomplete that corresponds to aerial photographs in certain years that cover only a portion of the study area.

The entire study area (river corridor, RC) was divided into 53 river segments (RS) of 1 km length (Fig. 2) (Stammel et al., 2021). The dimensions of the river corridor were based on the Q5 active floodplain area, representing the area inundated by a five-year return period flow, as this reflects the frequent and geomorphologically significant flood events shaping the river corridor, while also keeping the segments manageable in size and aligning with similar studies (Keele et al., 2019; Stammel et al., 2021). Therefore, each segment was approximately 1 km wide. This method resulted in a consistent study area covering the majority of the active floodplain.

For the manual vectorization of the study area, we used ArcGIS Pro (ESRI). We defined seven generalized LU/LC categories for the whole study period (1937–2020): arable land, permanent grassland, green area with floodplain forest, water bodies, river corridor, urban (built-up) area, and orchards (Fig. 4). These categories were applied to both black and white and colored versions of the aerial images (Fig. 5).

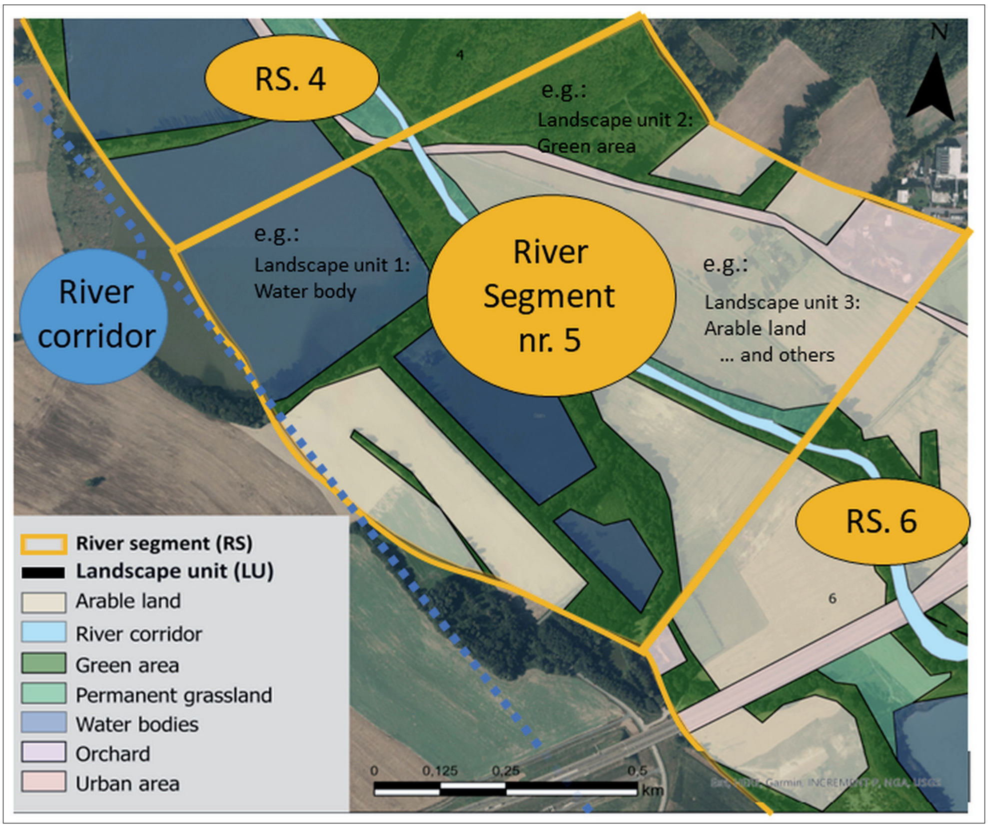

Fig. 4: Division of the study area of the river corridor (RC, blue dot line) into river segment (RS, orange line), and landscape unit (LU, black line), consisting of land use/land cover categories
Source: Authors' conceptualization and based on base map of the Czech Republic provided by State Administration of Land Surveying and Cadastre (Czech Republic)

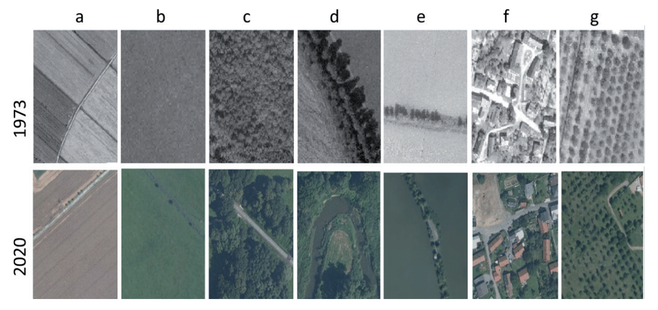

Fig. 5: All land use/land cover categories in 1973 (black and white version) and 2020 (color version): (a) arable land, (b) permanent grassland, (c) floodplain woods and green areas, (d) river channel corridor, (e) water bodies, (f) urban area, and (g) orchards
Source: Authors' conceptualization based on aerial images provided by Military Geographical and Hydrometeorological Office in Dobruška (Czech Republic) and orthophoto maps provided by State Administration of Land Surveying and Cadastre (Czech Republic)

The LU/LC categories were chosen to accurately reflect each type of LU/LC during the study period. Seven categories were used as the main types. Due to the variable quality of the maps, we have utilized a limited number of LU/LC categories. The selected categories encompass the key characteristics of the area; however, we acknowledge that, for instance, the 'water bodies' category could be further divided into natural water bodies, including wetlands, and artificial water bodies, such as ponds. Generalizing in this way reduced potential bias and allowed for more effective manual vectorization. Each identified category was manually outlined and classified into the corresponding vector layer (Głosińska & Lechowski, 2014). The vectorized and categorized maps were cross-checked by at least two researchers to minimize potential bias. We analyzed the LU/LC trend of the entire river corridor (1937 to 2020).

3.3 Ecosystem Services Assessment

Each river segment of the river corridor was analyzed to obtain more detailed information on ES. This process followed the framework of Burkhard et al. (2009), who developed a method to assess ES based on the LU/LC categorization. Keele et al. (2019), Podschun et al. (2018) and Stammel et al. (2021) created an assessment tailored for riverscapes that analyzes ES by land cover type and other relevant river characteristics (e.g., river width and channelization). We adjusted this approach to achieve higher precision. The ES assessed were considered typical and noteworthy for this study area and included all categories: potential agricultural ecosystem services and yield, natural flood mitigation, and water (including water purification, quality and provision). Each ES was analyzed separately according to the workflow (Fig. 1). Each analysis is discussed in detail. The results of LU/LC categorization and ES assessment were analyzed and visualized using Microsoft Excel and the R programming language.

The ES assessment was based on manually vectorized maps of the study area from 1937 to 2020 (n = 10) (see Section 3.2). A spatiotemporal and non-monetary ES valuation was chosen. Willemen (2020) noted that the limitation of this approach is that not all landscape features, qualities, and rarities relevant for ES assessment can be expressed by maps. To circumvent this limitation, we conducted fieldwork in the study area to verify the current state of the river, to understand the historical dynamics of the river and to gain deeper knowledge of the sociocultural relevance of the PLA. We used different indicators for each ES assessment (Appendix 1) We are aware that the list of ES assessed could be longer; however, we selected those that were considered key to our study area.

3.3.1 Potential Agricultural Ecosystem Services

We assessed the potential crop production and average agricultural yield (t/ha) for the river corridor and for each segment from 1937 to 2020. The potential agricultural ES were obtained from the RESI manual (Podschun et al., 2018). The river corridor was divided into arable land (AL) and permanent grassland land (PL).

We defined the site-specific yield potential for agricultural use (scale 0–94-points) for AL and PL separately. The data are open access and available from the Ministry of Agriculture as GIS layers (Ministry of Agriculture of the Czech Republic, 2021). Yield potential for agricultural use is based on many indicators, such as soil classification, climate, and slope. We have chosen to use a constant value of yield potential for the assessment period. According to Dolek (1990), the site specific agricultural yield potential based on field survey data from 1970 to 1980. In most cases, these data have not changed or been replaced by new data. We also checked the data on possible wind and water erosion in the study area, which could affect the agricultural yield potential. We found that our study area was not affected by soil erosion; therefore, we did not include this risk in our calculations. We did not include data from flood risk maps because data from 1937 to 1991 were not available or did not exist.

We then calculated the value for each RS based on the area of AL or PL and site-specific yield potential. The results were then classified into five categories (1 = very low, 2 = low, 3 = average, 4 = good, and 5 = very good). For detailed statistics and the following discussion, we also used results in percentages to increase the sensitivity to changes and the ability to interpret the data correctly.

We assessed the yield of AL based on the average yield of wheat and barley from the same year, specifically in the study area. We collected data on permanent grassland crops based on the average hay yield for the whole country, as it was difficult to find data specific to the region. National statistical books (from 1937 to 2020) were the sources of AL and PL. The yield for the river corridor was calculated as the sum of the product of the average yield and the areas of arable land and PL.

3.3.2 Natural Flood Mitigation

Our method for assessing natural flood mitigation ES was based on Keele et al. (2019) and Large and Gilvear (2015), with significant adjustments. We used four main indicators: roughness (R), palaeochannels and oxbow lakes (P_{ch}), riverbed sinuosity (S), and the coefficient of ecological stability (ES_{coef}), and A_{lu} corresponds to one land unit in the river segment (A_{RS}). It was calculated using the following formula (Equation 1 – Equation of Natural Flood Mitigation):

$$NFM_{RS} = \sum_{i}^{n} 0.5\,\frac{R_1 A_{lu_1} + \cdots}{A_{RS_1}} + 0.3P_{CH} + S + 0.4ES_{coef}$$

Roughness (Manning's roughness coefficient) was determined for the following individual LU/LC classes and varied between 0.03 and 0.12 (Chow, 1988). Palaeochannels and oxbow lakes had a positive effect on ES due to water retention, which enhances the natural dynamics in the lateral dimensions (Large & Gilvear, 2015). Sinuosity (index) is an important parameter of channel morphology that describes river patterns (from straight to meandering) (Wilzbach & Cummins, 2019). A meandering river has a greater capacity for flood mitigation than a channelized riverbed because a meandering river is connected to the floodplain; consequently, floodwater can be stored in the floodplain during overflow (Acreman et al., 2003; Kline & Cahoon, 2010), which is important for protecting downstream urban settlements (Watson et al., 2016).

The sinuosity for each RS was automatically calculated using the Meander Statistic toolbox (MSaT) to analyze the meander characteristics for each segment and study year (Ruben et al., 2021). The coefficient of ecological stability is the ratio of stable (natural) to unstable (artificial) landscape units in the RS. Stable landscape units include permanent grassland, green areas, water bodies, river channels, and orchards; unstable units include arable land and urban areas. Appendix 2 describes the equation and full procedure for the assessing natural flood mitigation, and we also describe the differences between Keele's et al. (2019) and our approach.

3.3.3 Water Ecosystem Services

Water ES include water purification (water quality) and water provision. We have chosen to use these two categories to provide a broader view, as there was insufficient data to identify a single category (as we have been looking at ES since 1937). Brauman et al. (2007) emphasized that water quality is an indicator of water purification and not of ES. Similar to previous ES analyses, the methodology was based on Large and Gilvear (2015) and Keele et al. (2019), with significant modifications as described in the Natural Flood Mitigation chapter. The used parameters for the calculation were the channel width (W_R), presence of palaeochannels (P_{ch}), ecological stability coefficient (ES_{coef}), green area coefficient of (GA_{coef}), and gravel bar coefficient (B_{coef}) and the formula is described in Equation 2 – Equation of Water Ecosystem Services:

$$W_{ES_{RS}} = \sum_{i}^{n} 0.5W_R + 0.3P_{CH} + 0.5ES_{coef} + 0.2GA_{coef} + 0.3B_{coef}$$

In Appendix 3 is available detailed description of calculation. River width (RW) is an important hydromorphological parameter that describes the area of the riverbed in contact with the flowing water and provides better potential for water purification. Since most of the study area belongs to a free meander section, we expect water purification potential to be high. The smaller regulated section still includes tributary inputs of mixed sediment and formations of gravel bars that could potentially play a role in the process. A wider channel indicates a greater volume of water supply in the bankfull state. In normal to minimal flows, wide channels are often associated with sediment deposition and gravel bar formations and heterogeneity of the river channel morphology (Witkowski, 2020). Paleochannels (Pch) and the ecological stability coefficient (EScoef) were characterized in the previous section. The green area coefficient (GAcoef) is the ratio of green area to the total area. The river bar coefficient (Bcoef) is the ratio of the area of the river bar to the area of the river channel. Gravel bars are accumulations of sediment of varying sizes that are typical of gravel-bed rivers and provide important habitat for many species, including riparian vegetation. The final categories (1 = very low, 2 = low, 3 = average, and 4 = high) were based on the quartiles of the values calculated for the whole river corridor and all the years assessed.

4. Results

4.1 General LU/LC patterns

The analysis of the trends of the representative LU/LC for each year showed that the dominant LU/LC in 1937 and 1949 was permanent grassland (Tab. 1). In 1955, arable land dominated, followed by permanent grassland and green areas. In 1985, the dominant type of LU/LC shifted to permanent grassland. The last change in the prevailing LU/LC type was in green areas, which changed in 2012. The trend of urban areas was increasing in all years considered, except in 1990 when there was a decrease of 9% in urban areas compared to the previous year. The reason for this change is discussed below. From 1937 to 1955, the coverage of urban areas was less than 300 ha; in 1985, it was 499.6 ha, and in 2020, it reached 876 ha. Other types of LU/LC, i.e., orchards, rivers, and water bodies, did not show any major changes. The first two types remained constant at 0.3% and 3% respectively.

Figure 6 shows the cumulative distribution of each LU/LC type in each segment. In this section, we describe the trends for each river segment (RS 1 to 53). In all assessment years, RS 1–9 were arable land with urban areas, and RS 10–16 were dominated by a mixture of arable land and permanent grassland, with additional green and urban areas. RS 17–34 were very dynamic, with the dominant arable land (1937–1955) being almost completely replaced by permanent grassland (1966–2020). In addition, the green area in these segments has increased significantly since 1990. RS 35–44 were dominated by water bodies and had low dynamics; since the 1970s, the protected landscape areas in these segments have been dominated by grassland and green areas. Finally, RS 44–53 were dominated by urban areas, which increased since 1949 and have remained stable since 2012.

4.2 Spatiotemporal variations in ecosystem services

4.2.1 Potential Agricultural Ecosystem Services

We assessed the potential agricultural ES of arable land and permanent grassland (Tab. 2). The potential agricultural ES of arable land was 1 (very low) in 1937, 1.5 in 1949, 2 (low) in 1955, and 1 (very low) in 1966–2020. In the case of permanent grassland, the category was 1.5 in 1937 and 1 (very low) in 1949–2020. The sum of the yields showed that there was no trend. Yields varied from year to year depending on climate and fertilizer use. The potential agricultural ES and the average yield (t/ha) of arable land showed a decreasing trend (especially from 1937 to 1973). Based on the potential agricultural ES of permanent grassland, the average value for the river corridor has fluctuated by about 15% since 1949.

Figure 7 shows the river segments in 1955, 1990, 2003 and 2020 that covering the whole study area. RS 1–9 achieved the highest potential values of all selected. In 1955, the category of RS 4–9 was 3 (average potential); segments 17–35 were classified as higher value segments. The trend of RS 35 was decreasing.

	Arable Land	T	Permanent Grassland	T	Green Area	T	Orchards	T	Urban Area	T	River	T	Water Bodies	T
1937*	1,364.9	-	1,904.3	-	373.7	-	6.2	-	228.9	-	94.7	-	193.2	-
1949*	935.3	-	949.5	-	397.7	-	2.3	-	224.6	-	101.9	-	47.4	-
1955	2,455.8	-	1,826.0	-	644.0	-	21.9	-	292.4	-	152.4	-	322.4	-
1966*	701.8	-	1,770.3	-	546.9	-	21.5	-	362.6	-	141.0	-	272.0	-
1973*	1,227.6	-	1,952.9	-	963.5	-	33.0	-	427.9	-	139.0	-	376.4	-
1985	1,197.8	↘	2,064.5	↗	1,225.7	↗	32.7	↘	658.2	↗	161.0	↗	381.1	↗
1990	1,271.5	↗	2,209.1	↗	1,136.5	↘	18.2	↘	499.6	↘	157.7	↘	424.0	↗
2003	1,171.0	↘	1,685.2	↘	1,503.8	↗	18.5	↗	785.4	↗	166.6	↗	389.5	↘
2012	1,131.7	↘	1,520.1	↘	1,604.1	↗	19.4	↗	873.6	↗	166.1	↗	400.7	↗
2020	1,137.7	↗	1,523.3	↗	1,586.8	↘	20.0	↗	876.3	↗	186.1	↗	400.7	↗

Tab. 1: Sum of each area (ha)
*Notes: T – trend, *year with uncomplete map cover*
Source: Authors' calculations

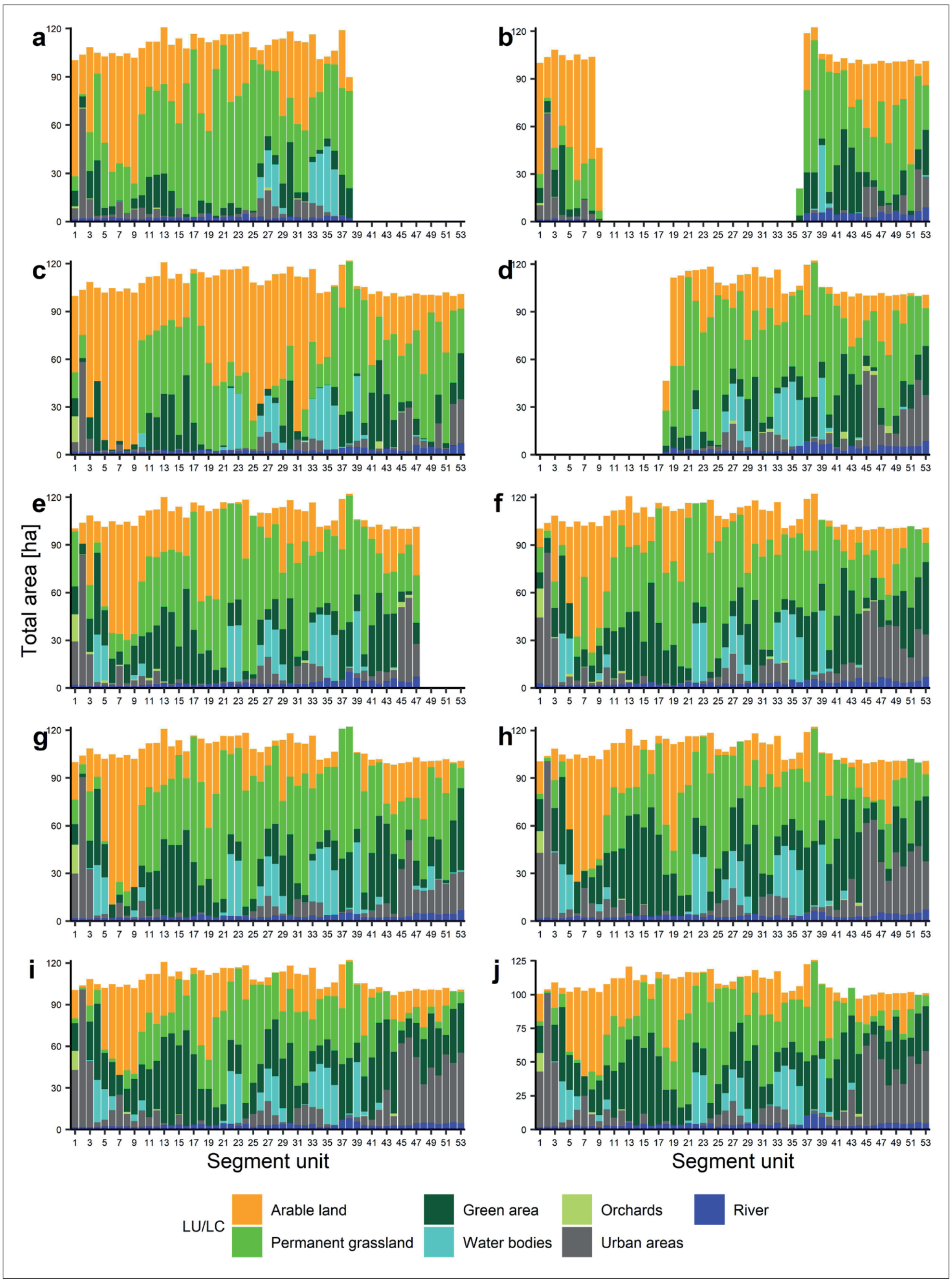

Fig. 6: Cumulative distribution of each land use/land cover type by river segment from 1937 to 2020. (a) 1937, (b) 1949, (c) 1955, (d) 1966, (e) 1973, (f) 1985, (g) 1990, (h) 2003, (i) 2012 and (j) 2020
Source: Authors' calculations

	1937*	1949*	1955	1966*	1973*	1985	1990	2003	2012	2020
Arable land										
Average category for the entire river corridor	1	1.5	2	1	1	1	1	1	1	1
Average % of river corridor	15%	28%	21%	8,8%	11.2%	9.3%	11%	9,6%	10%	10%
Average yield (t/ha)	1.98	2.18	2.52	2.51	3.60	4.99	5.58	3.87	4.25	5.66
Sum of yield (t/ha)	2,622	2,293	6,188	1,762	4,429	5,954	7,206	4,638	4,956	6,360
Permanent grassland										
Average category for river corridor	1.5	1	1	1	1	1	1	1	1	1
Average value for river corridor	19.4%	7.5%	14%	13%	15%	16%	17%	13%	12%	12%
Average yield (t/ha)	3.57	4.20	3.22	3.42	3.71	5.35	4.89	2.41	3.22	3.15
Sum of yield (t/ha)	6,798	3,949	5,877	5,970	7,167	11,040	10,802	4,060	4,895	4,820

Tab. 2: Results of potential agricultural ecosystem services
*Notes: *Year with uncomplete map cover*
Source: Authors' calculations

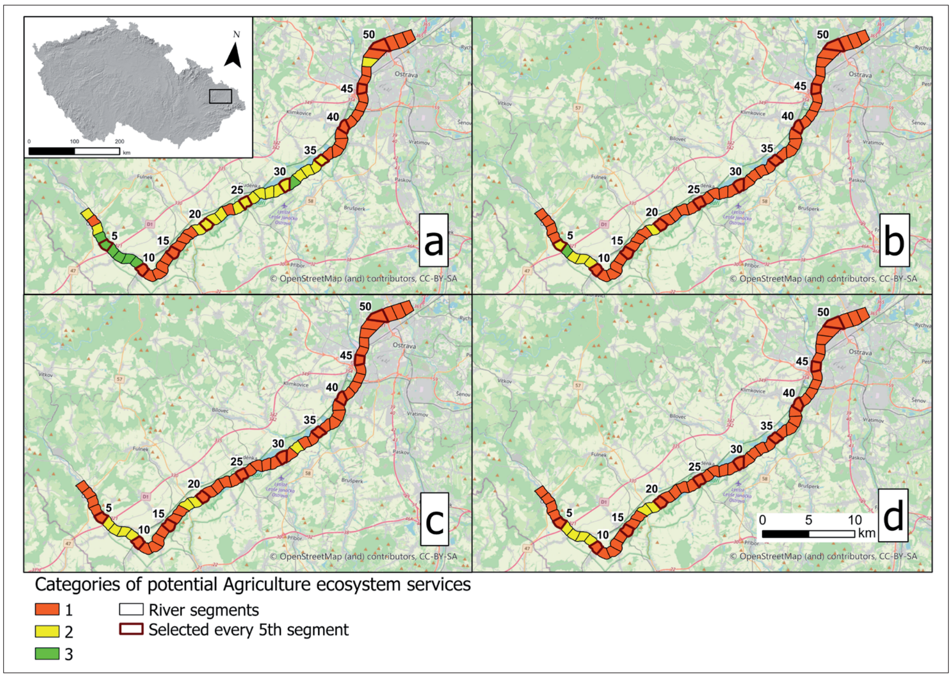

Fig. 7: Map of categories of potential agricultural ecosystem services in (a) 1955, (b) 1990, (c) 2003 and (d) 2020. Each category is based on the area values of AL and site-specific potential. Results range from 1 (very low) to 3 (average). From segment 8 to segment 44, PLA is placed
Source: Authors' conceptualization based on a base map and DEM of the Czech Republic provided by State Administration of Land Surveying and Cadastre (Czech Republic)

Figure 8 illustrates the potential agricultural ES on permanent grassland with a decreasing category trend in RS 10–15 and 47–51. In the middle of the study area, a few RS (e.g., 21–22, 31) showed category improvements from very low to low.

4.2.2 Natural flood mitigation ecosystem services

Natural flood mitigation ES increased from 1955 to 2003 and decreased slightly in 2020 (Tab. 3). Indicators of roughness and the coefficient of ecological stability showed increasing trends, and the trend of palaeochannels decreased after 1973. Sinuosity has been stable since 1973. An interesting trend can be seen when river segments are evaluated separately for each year (Fig. 9).

In all the years studied (1955, 1990, 2003, and 2020), the upstream (RS 1–10) and downstream (44–53) segments of the river had lower values (category very low – low) than the segments in the middle (RS 10–44) of the river reach (category average or high).

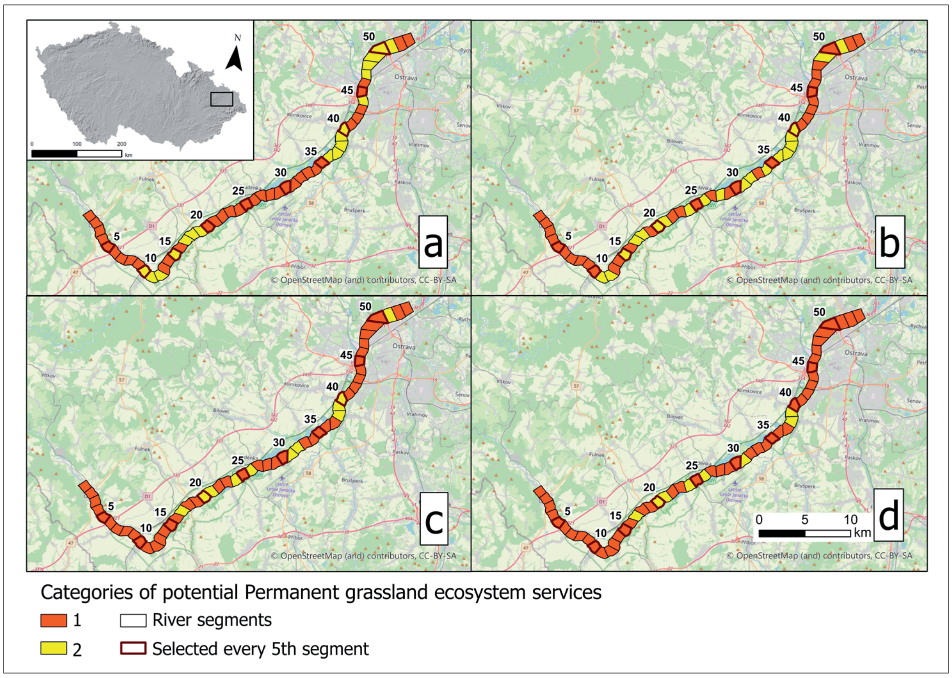

Fig. 8: Map of categories of potential agricultural ecosystem services on permanent grassland in (a) 1955, (b) 1990, (c) 2003 and (d) 2020. Each category is based on the area values of PL and site-specific potential. Results range from 1 (very low) to 2 (low). From segment 8 to segment 44, PLA is placed
Source: Authors' conceptualization based on a base map and DEM of the Czech Republic provided by State Administration of Land Surveying and Cadastre (Czech Republic)

Indicators	1937*	1949*	1955	1966*	1973*	1985	1990	2003	2012	2020
Roughness	60	50	91	71	96	128	116	194	197	199
Sinuosity	29.5	11	38	24	28.5	30	30	28	29.5	28.5
Paleochannels	53	27	87	72	93	91	85	58	74	71
Coefficient of ecological stability	149	95	180	156	195	218	220	214	215	212
Sum of final value°	135	89.1	181.6	143.5	182.4	208.5	201.5	228	236.2	234.1
Average category	2	2	2	3	3	3	3	3	3	3

Tab. 3: Results of natural flood mitigation service
*Notes: *Year with uncomplete map cover; °with added weight for each category*
Source: Authors' calculations

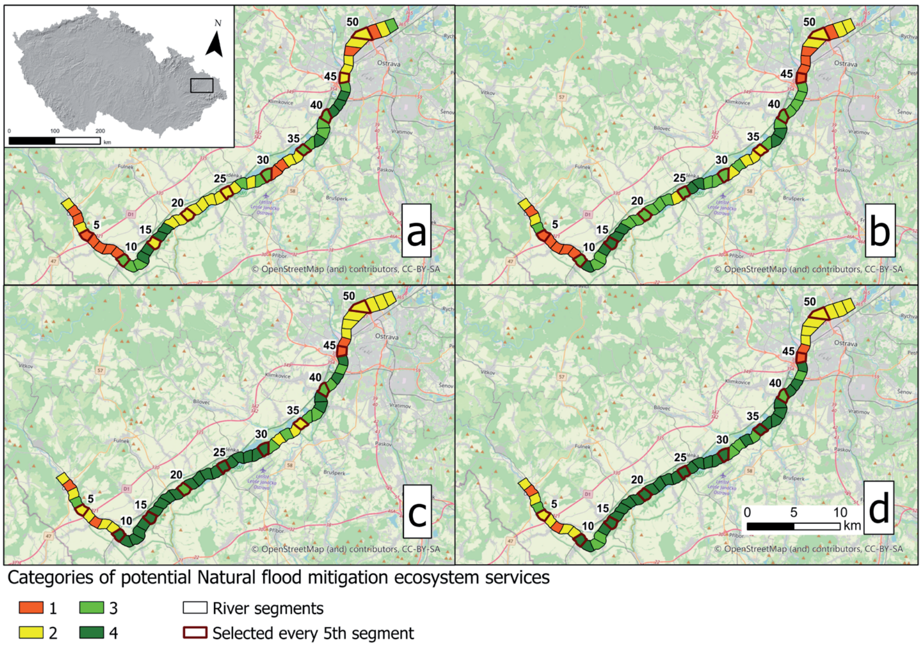

Fig. 9: Map of categories of natural flood mitigation in (a) 1955, (b) 1990, (c) 2003 and (d) 2020 (Notes: Each category represents a quartile of calculated ES values, ranging from 1 (very low) to 4 (high). From segment 8 to segment 44, PLA is placed)
Source: Authors' conceptualization based on base map and DEM of the Czech Republic provided by State Administration of Land Surveying and Cadastre (Czech Republic)

4.2.3 Water ecosystem services

Water ES exhibited an increasing trend from 1937 to 2020 (Tab. 4).

Figure 10 shows the trends of the river segments for each year. In 1955, the whole river corridor had a category of only 2 (low). The exception was RS 40–43, which had a category of 4 (high). These segments have been part of the Small Special Protection Area since the 1970s. The category was lower in the upstream segments of the river corridor (1–10) than in the downstream segments (RS 45–53); there could be several reasons for this. However, we assumed that the location of these upstream and downstream river segments in urban areas reduced the naturalness of the river reach.

5. Discussion

The data presented in this study show spatiotemporal trends in LU/LC and ES changes over the last 80 years, reflecting policy and societal changes. The dominant LU/LC reflects these policy shifts, namely agricultural and environmental protection. Until 1955, the dominant type was arable land, in 1985, permanent grassland and in 2012 green areas and floodplain forest.

5.1 LU/LC trends and policy in the last 80 years

In the assessed period from 1937 to 2020, we observed gradual changes in LU/LC. The dominant types were arable land (peak in 1955), permanent grassland (peak in 1985), and green areas, including floodplain forest (peak in 2012). We compared complete maps (representative, 1955, 1985–2020) and incomplete maps as additional data (1937, 1949, 1966 and 1973).

To understand the reasons for the change in LU/LC, it is necessary to look at the history of Europe and the Czech Republic and its landscape policies (namely, agricultural, urban, and environmental protection policies). Before the Second World War, this period was characterized by the capitalist model and democratic political parties (Grešlová Kušková, 2013). Maps from 1937 are characterized by the dominance of permanent grassland, followed by arable land, and small farmlands and orchards can be seen as a result of the agrarian reform (the reform had started in 1918 after the disintegration of Austrian Hungarian monarchy) focused on high and rational yields. The map of 1949 shows the beginning of the Communist Era. The easiest way to observe the expropriation of private land (Grešlová Kušková, 2013; Kupková et al., 2021) as state-owned arable land is through aerial images (Fig. 11).

The development of agriculture during the study period was related to mechanization. Human and animal labor was gradually transferred to machines; e.g., tractor performance doubled in just two decades after 1948 (Grešlová Kušková, 2013). The same trend can be observed in other Central European countries. Even in Austria, which was not part of the socialist bloc, Schirpke et al. (2023) noted that mechanization led to more dynamic changes in land use. Mechanization of processes led to cost-effective methods that accelerated yields but damaged the meadow ecosystem

Indicators	1937*	1949*	1955	1966*	1973*	1985	1990	2003	2012	2020
River width	56	57	95	88	88	108	100	115	109	105
Paleochannels	53	27	87	72	93	91	85	58	74	71
Coefficient ecological stability	149	95	180	156	195	218	220	214	215	212
Coefficient of Green Areas	41	43	67	65	104	136	127	165	174	172
Coefficient of river bars	67	68	63	60	68	97	76	106	79	92
Sum of final value°	146.7	113.1	195.9	174.6	209.1	246.6	233.7	246.7	242.7	241.8
Average category	2	3	2	3	3	3	2	3	3	3

Tab. 4: Results of water ecosystem service
*Notes: *Year with uncomplete map cover; °with added weight for each category*
Source: Authors' calculations

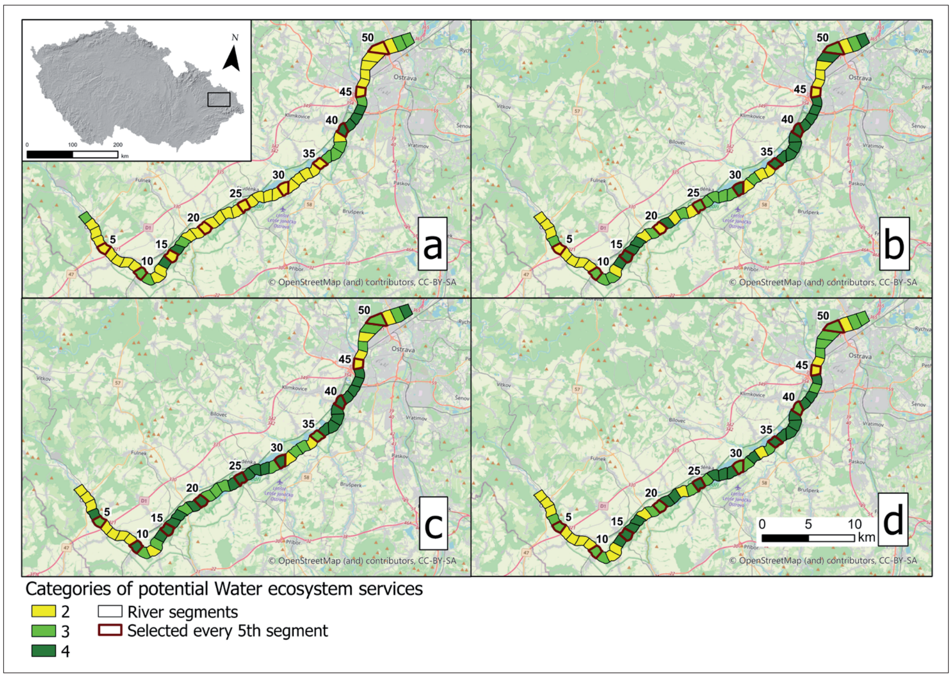

Fig. 10: Map of categories of water ecosystem services in (a) 1955, (b) 1990, (c) 2003 and (d) 2020 (Notes: Each category represents a quartile of calculated ES values, ranging from 2 (low) to 4 (high). From segment 8 to segment 44, PLA is placed)
Source: Authors' conceptualization based on base map and DEM of the Czech Republic provided by State Administration of Land Surveying and Cadastre (Czech Republic)

Fig. 11: Aerial images before (1937) and after (1955) collectivization during the Communist Era
Source: Authors' conceptualization based on aerial images provided by Military Geographical and Hydrometeorological Office in Dobruška (Czech Republic)

(Bartoš, 2011). The year 1955 is considered to be a peak of arable land, followed by a decline. According to Kupková et al. (2021), more than 90% of the Czech Republic has experienced a decrease in agricultural land. A comparison of LU/LC types between 1955 and 1985 (Fig. 6c and 6f) shows that production peaked in the 1980s, after which local agriculture was unable to compete with imported products (Grešlová Kušková, 2013). During this period, there was a steady decline in the emphasis on agriculture, and heavily cultivated areas were transformed into grasslands and forests and green areas. A similar trend was reported by Dolejš et al. (2019) for northern part of the Czech Republic (assessed from 1843 to 2013), and it is applicable to the whole of Central Europe, including Poland, Slovakia, which has a similar Communist Era (Bičík et al., 2001; Moravcova et al., 2022; Schirpke et al., 2023) In Austria, the decreasing trend started after the Second World War and in 1995, when the country joined the European Union, it escalated due to the inability to deal with imported products (Schirpke et al., 2023).

In the Czech Republic a landscape protection policy was established in the 1970–1980s (Kupková et al., 2021). In the study area, this was demonstrated by the establishment of the first natural reserves. In 1989, the political regime changed to a democratic one and global capitalism was applied (Bičík et al., 2001). Environmental protection started to be an important issue of the new political regime, which was concluded by the establishment of the Ministry of Environment (1989, including landscape policy and protection) (Kupková et al., 2021); however the power for a more progressive policy was gradually lost (Jehlička, 1999). In 1990, permanent grassland started to decrease in favor of green areas. In 1991, the Poodří PLA was established to specifically manage RS 7 to 43, and permanent grassland is still dominant in this part.

Urbanization is another important driver of change due to population growth and migration from small villages to cities. In particular, the city of Ostrava expanded throughout the 20th century. The same pattern can be found in the Austria, especially around larger cities undergoes strong urbanization (Schirpke et al., 2023). The results showed that the urban area in the study area gradually increased until 1990, when the growth started to decrease; however, the upward trend continued in 2003. The Communist Era boosted the urbanization process, especially around the city of Ostrava (the end of the study area) (Bičík et al., 2001; Kupková et al., 2021). Today, urbanization in the study area is not very high compared to other regions of the Czech Republic (Kupková et al., 2021), due to the formation of the Poodří PLA and the policy of the master plan and PLA zoning. The dynamic shifts in LU/LC types of the Odra River landscape were undoubtedly influenced by the country's policies and societal decisions. Schirpke et al. (2023) noted that urbanization and population growth is one of the main drivers of LU/LC change that can affect the provision of ES.

The assessment of historical changes in LU/LC faced certain limitations. The primary issue was the incomplete availability of aerial images for specific years (1937, 1949, 1966, 1973). Additionally, the quality of some images varied, that made detailed identification of LU/LC categories possible only on certain number of images. Consequently, the study was restricted to seven LU/LC categories. With complete datasets the number of categories would be larger.

5.2 Ecosystem services trends and challenges

The potential agricultural ES were calculated based on Podschun et al. (2018) and were highest in 1955 (21%; low category). In the following years, the category rapidly decreased to 9.3% (1985), and from 1990 to 2020, the values fluctuate around 10%. This corresponds to the trend in the whole country: agriculture expanded from the 1930s to the 1980s (Kupková et al., 2021). One of the reasons for the decrease in the ES score for agriculture is that the average area of floodplain forest and green areas has increased over the last 80 years. Watson et al. (2021) reported a peak in Dorset, southern England, in 1955 and a decreasing trend thereafter. Intensification of agriculture in Austria has also led to a decline of ES (Schirpke et al., 2023). The yield of arable land depends on many factors, including climate, the amount of fertilizer, and the use of pesticides. Fertilizer use increased from the 1950s to the 1990s in the Czech Republic (Grešlová Kušková, 2013) and from the 1950s to the 1980s in the UK (Watson et al., 2021). Thus, the trends were similar despite differences in political systems and agricultural policies. The potential agricultural ES in permanent grassland were highest in 1937, with a value of 19.4% (category 2, low), although this was assessed on an incomplete map (15 segments were missing). The value between 1955 and 2020 was approximately 14% (complete maps of the study area).

The ES of natural flood mitigation were assessed based on the Large and Gilvear (2015) and Keele et al. (2019). Similar to Grizzetti et al. (2015), we believe that assessing the ES of the river and its surrounding floodplain based on hydromorphological and landscape indicators is an effective method. In section 4.3, we list the differences between our study and the aforementioned studies (Keele et al., 2019; Large & Gilvear, 2015). Thorp et al. (2010) noted that different river patterns can provide different functions and ES. Our study area had two dominant river patterns: a straightened (channelized) and a meandering river. Generally, meandering rivers provide low to moderate benefits and services, whereas straightened rivers provide low benefits only. We have used Thorp's et al. (2010) constricted river pattern as a reference for a straightened river; thus, we assume that artificially adjusted rivers can provide less benefits and ES than natural rivers. Applying this approach to the study area, it is easy to detect which part of the river is meandering (middle part) and which part is channelized (beginning and the end of the study area). This pattern was not easy to detect in the 1955 water ES, but was detectable in the other years (1990, 2003 and 2020). The reason for the reduced detectability of water ES is that the sinuosity indicator was not included. There is a strong relationship between sinuosity and river patterns (Bravard & Petit, 2009).

The assessment of natural flood mitigation revealed that the very low (1) and low (2) categories were dominant at the beginning and end of the study period, whereas in the intervening years, the category was average to high. In 1955, segments 18–26 were in the low category due to the dominance of arable land. In the following years, the arable land was replaced by permanent grassland and green areas, which improved the category to average (3) and high (4), respectively. The same pattern was shown in Austria where the change of LU from arable land to grassland and forest increased the ES flood mitigation and erosion protection (Schirpke et al., 2023). The dominant category of water ES in 1955 was low (2), mainly because the prevailing category of LU/LC was arable land in the whole area. The exceptions were RS 36–37 and 40–44, where the category was average to high because these RS are the core area of the Poodří PLA. As the LU/LC types shifted towards more natural areas, the ES for water improved (Fig. 10). In 2020, the prevailing category of water ES was average to high.

5.3 Poodří Protected Landscape Area: protection success?

The creation of the Poodří Protected Landscape Area was proposed in 1975 but was rejected by the political regime (Jarošek, 2021). Partial success was achieved in the 1970s and 1980s with the creation of smaller protected landscape areas (Natural Reservation Polanský Les (1975) and Polanská Niva (1985)). The object of protection is the natural and near-natural ecosystems of the Odra River and its floodplain, including the lower sections of its tributaries and river terraces, and the associated flora and fauna of river floodplains and wetland biotopes (Nature Conservation Agency of the Czech Republic, 2009).

In general, the communist period and agricultural policies changed and damaged the landscape of the Czech Republic, including Poodří (Grešlová Kušková, 2013; Kupková et al., 2021). Before 1948, meadows were grazed by livestock or mown by hand, but after 1948, some were converted to arable land or mown by machine. This led to a decline in species-rich ecosystems. The species-rich alluvial meadows of the Odra floodplain were replaced by arable land or by more progressive grass species occupying the open niches (Jarošek, 2021). Flynn et al. (2009) pointed out that simplified agricultural ecosystems lead to a loss of species richness and most endanger unique species. The smaller areas of arable land were connected to create larger productive blocks (Fig. 8), and large amounts of fertilizer were used (Bartoš, 2011). All of these changes affected the hydrological regime and water quality.

The challenge of the last 30 years has been to restore these species-rich floodplain meadows through specific management, e.g., manual mowing at least twice a year or different mowing dates (Jarošek, 2021). At present, the landscape and its ecosystem are threatened by changing climate (heavy rainfall on the one hand and low flow on the other hand) and the expansion of alien species such as Reynoutria sp. or Helianthus tuberosus, which could damage the Poodří ecosystem without human intervention (Bartoš, 2011).

In terms of ES from 1937 to 2020, natural flood mitigation and water showed increasing trends; in contrast, the trend of potential agricultural ES of arable land and permanent grassland decreased after 1949. The categories of ES varied from very low to low for potential agricultural ES and from low to high for natural flood mitigation and water ES. Compared to similar studies, we monitored the study area at a more detailed scale and over a longer period. Understanding the historical patterns that lead to the declines in ES can help identify problems. This allows environmental managers to address the situation more quickly and policies can be changed or adopted accordingly.

Figure 12 shows the changes in natural flood mitigation and water ES after the creation of the Poodří PLA. These ES remained the same or increased in the following years due to the natural shift of the LU/LC.

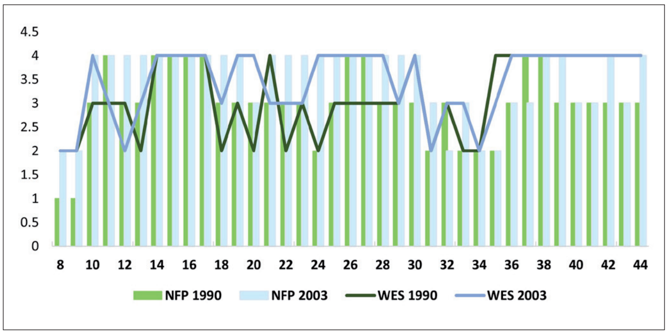

Fig. 12: Categories of natural flood mitigation (NFP) and water ecosystem services (WES) before and after the establishment of the Poodří PLA. Source: Authors' calculations

6. Conclusions

Over the past 80 years, political changes and implementation of environmental policies have been the main drivers of LU/LC change in the study area. Initially, from 1937 to 1955, arable land dominated, with negative impacts on ecosystem services. The Communist Party's agricultural intensification and collectivization efforts, starting in 1948, exacerbated this trend, a pattern observed throughout Central Europe. By 1985, the decreasing competitiveness of the agricultural sector had anticipated the political transformations of 1989. These transformations subsequently resulted in advancements in environmental policies, which preceded improvements in ecosystem services, particularly regarding natural flood protection and water-related services. The establishment of the Poodří PLA in 1991 preserved the Odra River in its natural state and improved the quality of ES.

In this respect, the study provides valuable data on the continuous monitoring of ES in the Poodří PLA, illustrating the positive impact of landscape protection policy. The comparison between 2012 and 2003 highlighted the effects of urbanization pressure and natural grassland overgrowth. Our results underline the importance of the Poodří PLA in stabilizing the region's landscape and improving ES and serve as a compelling example for advocating new protected areas. Future efforts should focus on maintaining these high ES levels in the face of political change, extreme weather, urbanization.

Future research should focus on understanding the combined effects of land-use change, urbanization, and climate change on the dynamics of ES in protected areas. In particular, investigating how changes in agricultural practices, natural grassland cover and extreme weather events affect flood protection and water provision, and quality services would provide valuable insights. Furthermore, studying the socio-economic drivers of land use change in different policy contexts could help predict future trends and inform policy decisions for better land management and conservation strategies.

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Data accessibility

The data sets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Appendices

Appendix 1: Indicators used for the ecosystem services assessment
*Notes: # = number of ordinal classes, * = will be discussed separately, RS = river segment*

Name of indicator	#	Description of ordinal classes of RS
Area of the segment	none	Classes defined by number and extent of different categories
Channel width	10	Classes defined by measured width
Sinuosity	3	Classes defined by calculation of sinuosity
Paleochannels	4	Classes defined by calculation quantity of paleochannels
Coefficient of Green Areas	10	Classes defined as a proportion to the total segment area
Coefficient of river bars	10	Classes defined as a proportion to the total segment area
Roughness of area	4	Classes defined by number and extent of different categories
Ecological stability ratio	4	Classes defined by area of ecological stable stage
Yield potential	96	Classes defined by categories
Cultural elements	5*	Classes defined by number and extent of different categories

Appendix 2: Process of calculation of Natural Flood Mitigation ES

Name of Ecosystem Service	Abbr.	Description		
Natural Flood Mitigation Provisioning category	NFM	Natural flood protection based on the river and floodplain LU/LC characteristics		
Indicator	**Abbr.**	**Unit**	**Variable description**	**Data basis**
Roughness of the segment	R	Manning's value	Roughness of each LU/LC unit	Tables Calculation
Paleochannels	P_{ch}	-	Number and size of P_{ch} at each segment	Map analysis
Sinuosity	S	-	Calculated sinuosity for each segment	Map analysis Calculation
Coefficient of ecological stability	ES_{coef}	-	Calculated sinuosity for each segment	Statistical Office

Equation of Natural Flood Mitigation: $$NFM_{RS} = \sum_{i}^{n} 0.5\frac{R_1 A_{lu_1} + \cdots}{A_{RS_1}} + 0.3P_{CH} + S + 0.4ES_{coef}$$

The resulting service is the product of the sum of four variable. The numbers 0.3, 0.4 and 0.5 are weights for each variable determined by expert estimation for the study area. The final categories of Natural Flood Mitigation (1 = very low, 2 = low, 3 = average, and 4 = high) were based on quartiles of the values calculated for the entire river corridor and all assessed years (see Table below).

Category			
very low <2.7	low 2.7 to 3.8	average 3.8 to 4	high >4
1	2	3	4

Roughness (Manning's roughness coefficient) was determined for the following individual LU/LC classes: arable land (0.04), permanent grassland (0.035), green areas (0.12), water bodies (0.03), river channel (0.03), orchards (0.1), and urban area (0.05) (Chow, 1988).

Compared to Keele et al. (2019) and Large and Gilvear (2015), we (i) used ArcGIS Pro instead of the Google Earth platform; (ii) measured each landscape unit instead of estimating the percentage cover in the defined river corridor; (iii) used less detailed land cover types because some categories in our study were missing and precision of work can be affected by aerial image quality (more than 50% of aerial images are black-white); (iv) used Manning's value to describe the roughness of different landscape units to achieve more accurate data; (v) used ecological stability; and (vi) based the final categories on quartiles of the values calculated for the whole river corridor and all assessed years. The final score of ES Natural Flood Mitigation is the sum of all listed parameters corresponding to the equation (Tables 3 and 4) for each river segment.

The sinuosity for each RS was automatically calculated using the Meander Statistic toolbox (MSaT) to analyze the meander characteristics for each segment and studied year (Ruben et al., 2021). This software provides a comprehensive analysis of the input river centerline in the form of point coordinates.

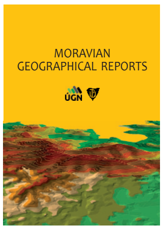
Appendix 3: Equation of Water Ecosystem Service

Name of Ecosystem Service	Abbr.	Description		
Water Ecosystem Services Provisioning category	NFM	Natural flood protection based on the river and floodplain LU/LC characteristics		
Indicator	**Abbr.**	**Unit**	**Variable description**	**Data basis**
River width	WR	Manning's value	Roughness of each LU/LC unit	Tables Calculation
Paleochannels	P_{ch}	-	Number and size of P_{ch} at each segment	Map analysis
Coefficient of ecological stability	ES_{coef}	-	Calculated sinuosity for each segment	Statistical Office
Coefficient of Green Areas	GA_{coef}	-	Ratio stable and unstable landscape unit in segment	Map analysis Calculation
Coefficient of river bars	B_{coef}	-	Ratio of area of river bar to river segment length and width	Map analysis

Equation of Water Ecosystem Services: $$W_{ES_{RS}} = \sum_{i}^{n} 0.5W_R + 0.3P_{CH} + 0.5ES_{coef} + 0.2GA_{coef} + 0.3B_{coef}$$

The resulting service is the product of the sum of four variable. The numbers 0.2, 0.3 and 0.5 are weights for each variable determined by expert estimation for the study area.

Category			
very low <3.2	low 3.2 to 4.1	average 4.1 to 4.9	high >4.9
1	2	3	4



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Natura 2000 sites as a crucial part of nature conservation? An analysis of landscape development in selected areas of the Czech Republic

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Abstract

The Natura 2000 network is the key tool for preserving biodiversity in the EU. However, such a system of territorial protection is under increasing anthropogenic pressure and sites with no national designation are managed rather insufficiently across Europe. Therefore, we investigated six selected large areas consisting of Natura 2000 sites in the Czech Republic, which are not designated as national large-scale protected areas, analysed their landscape development over the last 70 years, and considered their suitability for establishment as national protected areas. All studied Natura 2000 sites have suitable conditions to become national protected areas; lower anthropogenic pressure than in current nationally protected areas and also natural and close-to-natural land cover in the vast majority of the areas. Moreover, designation of these areas as nationally protected areas could contribute significantly to ensuring connectivity between protected areas and could enhance proper management of the areas, which is especially needed in some valuable but vulnerable regions.

Keywords: Natura 2000, Czech Republic, protected areas, land cover, landscape fragmentation and connectivity, anthropogenic pressure

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1. Introduction

Protected areas (PAs) are a cornerstone of protecting nature around the world. PAs are designated as a tool to halt biodiversity loss and enhance the ecological functions of landscape and conditions of habitats (Watson et al., 2014). In the European Union (EU), the Natura 2000 network is the largest ecological network and a key part of the EU´s Biodiversity strategy (European Commission, 2021). Natura 2000 is based on the Birds Directive from 1979 (79/409/EEC; European Council, 1979), with designation of Special Protection Areas (SPA), and the Habitats Directive from 1992 (92/43/EEC; European Council, 1992), spatially defined as Sites of Community Importance (SCI) by member states and, after European Commission approval, designated as Special Areas of Conservation (SAC). Natura 2000 sites are established to protect selected species and habitats and to be coherent across the EU. This framework stresses sustainability and effective and careful management to achieve goals regarding the subject of protection, but no strict conservation measures are needed (European Environmental Agency, 2012). Now, the Natura 2000 network covers around 19% of the EU (European Environmental Agency, 2024).

However, despite their aims to protect habitats, Natura 2000 sites are experiencing negative changes, which are similar to the surrounding landscape. Indeed, it was found that Natura 2000 sites are dynamic parts of the landscape with change recorded on 20% of their area between 1990 and 2012 (Guerra et al., 2019; Hermoso et al., 2018). Generally, artificial or intensively used areas (e.g. buildings, roads) in Natura 2000 sites have increased (Kubacka & Smaga, 2019) but at a lower rate than outside of the Natura 2000 sites (Kallimanis et al., 2015). In order to halt this negative trend, suitable and sustainable management is crucial for finding appropriate measures, which can vary over time (Kovac et al., 2018). Thus, one of the important research topics deals with monitoring the rate and type of landscape changes caused by different management regimes in and around Natura 2000 sites.

In the Czech Republic, 14% of land is protected as Natura 2000 sites (European Environmental Agency, 2024). Like in other parts of Europe, Central European and Czech Natura 2000 sites have experienced anthropisation (an increase of man-made structures) and land-use intensification (Concepción, 2021; Hermoso et al., 2018; Mammides et al., 2024). This is in accordance with

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general trends in Czech landscape recorded over the past century and has been driven in particular by political and socio-economic events (Kupková et al., 2013).

In some EU countries, and also in Czech environmental law, Natura 2000 sites do not have such strict protection status as nationally designed Protected Landscape Areas (PLA) or even National Parks (NP). Management in Natura 2000 sites allows economic activities except those harmful for the purpose of protection. As documented by Křenová and Kindlmann (2015) and Miklín and Čížek (2014) implementation of Natura 2000 in Czech Republic can be suboptimal due to unstable political conditions and the weak position of state representatives. The success of management and protection also largely depends on ownership of property and common agreement of all stakeholders. The protection of Natura 2000 sites is rather focused on certain species and habitats, not on the ecosystem or landscape as a whole (European Commission, 2015). Natura 2000 sites also sometimes lack clear management plans (Martínez-Fernández et al., 2015). Management of Czech Natura 2000 sites is not zoned and management plans are relatively brief in comparison with PLA and NP management plans (Czech National Council, 1992). In addition, there currently exists no EU-wide regulation strictly preventing new infrastructure from being built inside Natura 2000 sites. Prevention of new infrastructure within Natura 2000 sites is thus left to regulation and enforcement at the local and national level (Kenig-Witkowska, 2017).

2. Theoretical background

Land cover changes in the Natura 2000 sites around the EU have been widely examined (e.g. Mücher et al., 2009; Mallinis et al., 2011). Natura 2000 sites experienced higher urbanisation (and lower landscape stability) than nationally designated PAs in Spain (Martínez-Fernández et al., 2015). A study researching Natura 2000 sites across the EU revealed that more than 20% of the landscape in these sites has changed in the last two decades (Hermoso et al., 2018). Moreover, older and steeper Natura 2000 sites were transformed towards natural land cover, whereas recently established and flatter ones were changed to more artificial cover and the landscape structure of all sites has become homogenised (Hermoso et al., 2018). The threat of homogenisation is related to land-use intensification on the one side and abandonment on the other (Anderson & Mammides, 2020).

However, changes are still larger and management of farmland worse in the surroundings of Natura 2000 sites than within them (Anderson & Mammides, 2020; Hermoso et al., 2018). More than half of Natura 2000 sites in Europe (58.5%) are less fragmented than their surroundings (especially in remote and mountainous regions). In contrast, within EU countries, France, Belgium, the Netherlands, Luxembourg, Germany, and the Czech Republic show the highest level of fragmentation inside and around Natura 2000 sites (Lawrence at al., 2021); moreover, landscape fragmentation in the Czech Republic has been increasing (Romportl, 2017). Furthermore, smaller Natura 2000 sites are more vulnerable to change (Concepción, 2021; Hermoso et al., 2018). Therefore, larger and fewer, rather than more and smaller, Natura 2000 sites covering underrepresented species should be preferred during the designation process (Concepción, 2021; Gruber et al., 2012).

From a landscape change point of view, the Czech landscape shows different developments in the periphery and core areas. Peripheral parts of mainly mountainous regions along the border in the south, west, and north of the Czech Republic were abandoned after World War II due to the expulsion of Czech Germans. Furthermore, the communist regime restricted entry to the border areas. These facts subsequently led to afforestation and extensification of agriculture (Kupková et al., 2021). On the other hand, in more fertile core regions, agriculture was collectivised and intensified with consequences for land use and landscape structure (Bičík & Jančák, 2001; Sklenička et al., 2014). After the fall of communism in 1989, less favoured areas for agriculture, mostly found in the periphery, experienced ongoing extensification in the form of afforestation and grassing over (Feranec et al., 2010; Kupková & Bičík, 2016), while ongoing intensification of agriculture and urbanisation is present in lowlands and surroundings of large cities, representing core areas (Kupková & Bičík, 2016; Kupková et al., 2021; Pazúr et al., 2017).

In this study, our aim was to focus on landscape changes (land cover and anthropogenic structures) and landscape fragmentation that occurred during the past 70 years in selected larger Natura 2000 sites without any additional national protection to analyse landscape stability and anthropogenic pressure. Studying landscape changes together with fragmentation in these sites can help in deciding whether these sites a) can strengthen ecological stability and landscape connectivity across the Czech landscape, thus helping in preserving biodiversity and increasing gene flow, and therefore b) are good candidates for national designation with stricter protection, like national parks and protected landscape areas. Although studied sites were declared in 2005, we studied landscape changes since 1950s in order to capture long-term landscape stability, which can be used as a proxy for capturing the level of habitat quality, and subsequently to host biodiversity (Fraser & Pouiliot, 2009).

We evaluated selected study localities, which so far have not been assessed in more detailed way, based on whether they have experienced similar changes as other Natura 2000 sites in the EU or not, focusing on: changes of land cover, land-use intensification, and anthropisation.

Based on this, we hypothesised that:

1. The studied Natura 2000 sites have been more affected by urbanisation and land-use intensification according to European findings (Anderson & Mammides, 2020; Concepción, 2021; Hermoso et al., 2018; Martínez-Fernández et al., 2015) than Czech PLA and NP (Janík et al., 2024).
2. Selected study localities within Natura 2000 sites are, regarding the past 70-year period, rather favourable for national PA designation as they have similar characteristics as current PLAs and NPs (Janík et al., 2024) and due to their location (Feranec et al., 2010; Kupková & Bičík, 2016) they can serve as crucial stepping stones for increasing ecological connectivity and biodiversity; however, we expect that nationally designated PAs (PLAs and NPs) are more ecologically stable (stability of natural and close-to-natural land cover categories) without significant negative changes (see e.g. Martínez-Fernández et al., 2015).

3. Data and methods

3.1 Study area

We grouped the selected Natura 2000 sites into six localities and excluded parts that are already inside a PLA or NP (Tab. 1). The framework of Natura 2000 does not exclude human activities from the landscape. Paradoxically, it can lead to a more diverse landscape; for example, Boletice, Doupovské hory Mts., and Libavá, which are situated in mid and higher elevations, have been military areas (established after World War II) since the beginning of our study period. Bzenecká Doubrava – Strážnické Pomoraví and Soutok are located in South Moravia in the lowlands and combine forests and agricultural land along large rivers. Krušné hory Mts. is a mountainous locality affected by depopulation after World War II and significant air pollution from coal-fired power stations. On the other hand, Krušné hory Mts. can be depicted as a large piece of landscape with ecologically valuable sites.

Study localities range from lowlands (Bzenecká Doubrava – Strážnické Pomoraví, Soutok) to mountainous ridges (Boletice, Krušné hory Mts.) and are situated across the whole of the Czech Republic (Fig. 1)

3.2 Land cover

Land cover data were created by manual vectorisation in ArcGIS 10.x (ESRI, 2020) using available georeferenced and scanned topographic maps and aerial imagery to capture the most significant events of landscape development in the last seventy years. They were created for four periods and made it possible to detect changes between them:

1. 1950 dataset represents period of changes in open agricultural land, such as the expansion of arable land in more fertile regions based on land reforms from the beginning of the 20th century, as well as the introduction of new technologies (Kupková et al., 2021) and abandonment of mostly border areas formerly inhabited by Czech Germans, who were expelled after the Second World War (Havlíček et al., 2022), predominantly resulting into afforestation (Lipský, 2001). Land cover from this period was based on 1:25,000 Czechoslovak military maps from 1952–1956 (General Staff of the Czechoslovak Army 1952–1956).
2. 1990 dataset shows a time of change from communism with large-scale landscape exploitation, ranging from intensified agriculture and destruction of small landscape features caused by socialist collectivisation (Sklenička et al., 2014; Skokanová et al., 2016), to industrialisation and the spread of large open mines (Kupková et al., 2021) and to democracy and capitalism with rapid suburbanisation and extensification (in the form of afforestation as well as grassing over) of less favourable regions, mainly the mountainous ones (Grešlová et al., 2023). The land cover layer from this period was based on 1:25,000 Czechoslovak military maps from 1988–1995 (General Staff of the Czechoslovak Army 1988–1995).
3. 2004 dataset shows the year of accession into the EU, accompanied with changes in agricultural subsidies and other restrictions, such as restricted land purchases and land quotas on various types of cultivated crops, which led to a decrease in agricultural production, extensification, and land abandonment (Kupková et al., 2021) on one hand, and spread of specific types of crops (e.g. vineyards) before this date (Skokanová et al., 2020) on the other. Land cover data from this period were vectorised from a 1:10,000 base map originating between 2002 and 2006 (Czech Office for Surveying, Mapping and Cadastre 2002–2006) and aerial imagery from 2003 and 2005 with pixel size 0.5 m (Czech Office for Surveying, Mapping and Cadastre 2003–2005).
4. 2016–2020 dataset represents the current state, with ongoing urbanisation and growing pressure from recreational use (Janík et al., 2021). Land cover data are based on aerial imagery with pixel size 0.2 m (Czech Office for Surveying, Mapping and Cadastre 2016–2020) and supported by LPIS (Land Parcel Information System – Soil registry; Ministry of Agriculture 2016–2020).

Name of area	Type and number of included Natura 2000 site	Area [km^2]
Boletice	1 SAC, 1 SPA	101.25
Bzenecká Doubrava – Strážnické Pomoraví	1 SPA	117.23
Doupovské hory Mts.	1 SAC, 1 SPA	620.12
Krušné hory Mts.	3 SAC, 2 SPA	573.54
Libavá	1 SAC, 1 SPA	327.24
Soutok	2 SAC, 1 SPA	128.39

Tab. 1: Study localities
Source: AOPK ČR / NCA (Nature Conservation Agency of the Czech Republic)

Land cover data were captured as polygons larger than 0.8 ha and wider than 40 m. This procedure ensured the same level of generalisation from sources with different spatial scale (topographic maps in scales 1:10,000 to 1:25,000 and aerial photographs with pixel sizes from 0.5 m to 0.2 m). Given the different sources that are able to capture land cover types in different detail, and to make the corresponding land cover maps

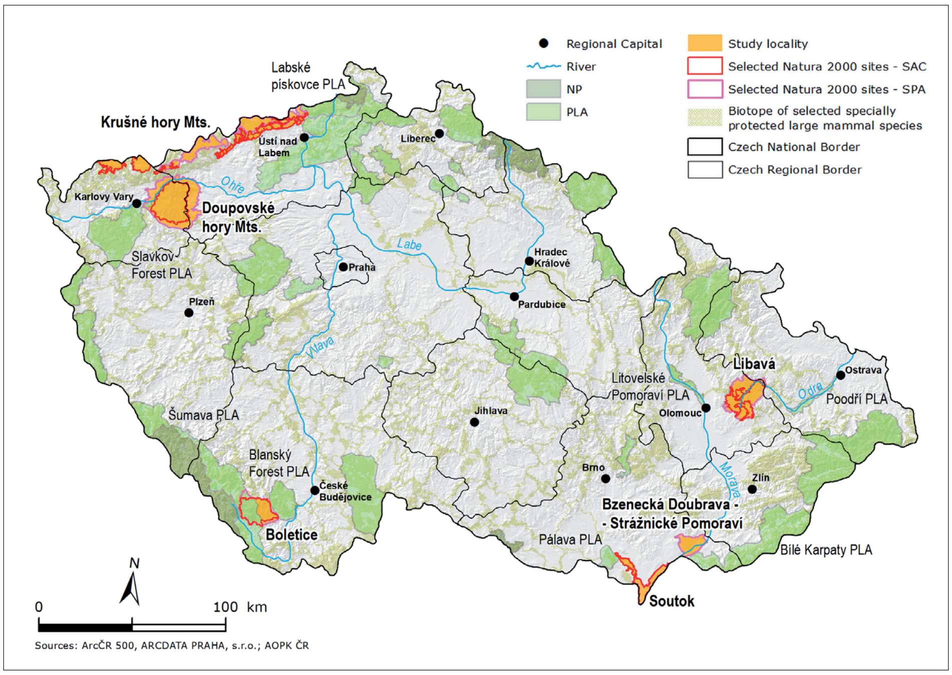

Fig. 1: Study localities and other large-scale nationally designed PAs and Biotope of selected specially protected large mammal species. Study localities are situated between current PLAs and NPs (Krušné hory Mts. and Doupovské hory Mts. are between Labské pískovce and Slavkov Forest, Boletice is between Šumava and Blanský Forest, Libavá is between Litovelské Pomoraví and Poodří and Soutok with Bzenecká Doubrava are between Pálava and Bílé Karpaty, see the description in the map) and their names are stated in larger bold font
Source: ArcČR 500 ARCDATA PRAHA, s.r.o.; AOPK ČR / NCA (Nature Conservation Agency of the Czech Republic)

comparable, only nine main land cover categories were identified (Tab. 2), based on the combination of used map keys and legends (Mackovčin, 2009; Skokanová, 2009).

Arable land is defined as a land used mainly for agricultural production of cereals, legumes, oil crops, root crops, and technical crops. It also includes a mosaic of arable fields with small vineyards, trees and meadows, and fallow land. Permanent grassland includes all types of permanent herbaceous vegetation, regardless of their composition. As such, this category includes also wetlands, which, while potentially distinguishable in orthophotos, are usually depicted in the maps as grasslands. Gardens and orchards include mainly extensive as well as intensive orchards in the landscape. However, some orchards can be close to settlements and might therefore be seen as large gardens, especially in orthophotos. Unfortunately, the maps used have the same symbol for both large gardens and orchards, making them undistinguishable from each other. Therefore, they are grouped together. Vineyards and hop-fields are included in a separate category in order to capture this specific, and rather unique, land cover class. The forest category includes all larger wooded plots, regardless their type and stage.

Water areas are represented by all types of water bodies, i.e. with a permanent level of above-ground water.

Built-up areas include all types of residential, industrial, commercial, agricultural, transportation, administrative or military structures and social facilities with adjacent small gardens and other forms of green plots. Recreational areas are categorised as areas used mainly for recreation and tourism outside settlements with distinct man-made features, such as sheds and wooden structures (in the case of garden allotments and campsites), playgrounds (for sport resorts), cages (zoological gardens), holes, sand features and rocks (golf courses) or distinctive and dense paths in, for example, wooded plots (in the case of spas). In the maps, they are usually marked by abbreviation (e.g. golf, rekre, zoo, etc.). Other areas are anthropogenic features in the form of mining areas, usually as open mines, or dump sites, i.e. features of unused land.

While forest and permanent grassland represent natural and close-to-natural and more ecologically stable land cover categories, built-up areas, recreational areas and other areas can be seen as anthropogenic categories, with arable land, gardens and orchards, and vineyards and hop-fields being grouped into agricultural use. Water areas could be both natural and artificial, so they were excluded from this distinction of aggregated natural and anthropogenic land cover categories (see Tab. 2).

Polygon layers capturing land cover distribution in each period enabled calculating shares of land cover categories and selected landscape metrics, namely edge density (ED) and Shannon diversity index (SHDI). Both landscape metrics can capture simplification of the landscape caused by different processes and driving forces behind them. ED highlights change of patch shape while SHDI illustrates diversity of represented land cover categories and their relative distribution (Rempel et al., 2008). Both landscape metrics as well as shares of land cover categories were calculated in Patch analyst extension for ArcGIS (Elkie et al., 1999).

To capture main processes of change in the terms of largest growths and decreases, as well as stability, of land cover (i.e. if the land cover class of a given patch did not change in any given period), the polygon layers were overlaid, resulting in a GIS database. The main processes or land cover flows (European environmental agency, 2006; Feranec et al., 2010; Martínez-Fernández et al., 2015; Zbierska, 2022) were calculated between two adjacent periods (e.g. 1950 and 1990) as transitions of land cover classes to arable land, permanent grassland, forest or built-up areas.

To compare differences between selected land cover characteristics, in particular area of individual land cover categories and their stability calculated for NATURA 2000 sites and average values of these characteristics calculated for 4 NP and 26 PLA and to test significance of these differences, Wilcoxon signed rank, a non-parametric, test in R (R core team, 2023) was used.

3.3 Anthropogenic structures and landscape fragmentation

Anthropogenic pressure is a threat for biodiversity and landscape resilience. Therefore, we analysed it separately in more detail. Anthropogenic pressure is defined for this study as physical anthropogenic structures and their impact on landscape fragmentation. We prepared data of anthropogenic structures in the selected study areas for similar temporal milestones using the following historical sources:

1. 1960 dataset: 1:10,000 topographic map from 1957 to 1971 (Central Administration of Geodesy and Cartography 1957–1971) with support of aerial images from the 1950s;
2. 1990 dataset: 1:10,000 base map originating between 1986 and 1995 (Central Administration of Geodesy and Cartography 1986–1995);
3. 2004 dataset: 1:10,000 base map originating between 2002 and 2006 (Czech Office for Surveying, Mapping and Cadastre 2002–2006) with support of aerial imagery from 2003 and 2005 with pixel size 0.5 m (Czech Office for Surveying, Mapping and Cadastre (2003–2005);
4. 2016–2020 dataset: current data was obtained and edited from ZABAGED® (The Fundamental Base of Geographic Data of Czech Republic) and aerial imagery with pixel size 0.2 m (Czech Office for Surveying, Mapping and Cadastre 2016–2020).

As for land cover, data for analysing anthropogenic pressure were derived manually in ArcGIS 10.x (ESRI, 2020) based on the above-mentioned data sources. Built-up and recreational areas were processed as polygon layers with a minimum mapping unit of 0.2 ha (higher resolution than in land cover data). Built-up areas consisted of buildings, urban areas, fenced estates, and gardens around houses. Recreational areas were recognised as camp sites, golf courses, playgrounds, ski slopes, shooting ranges, tracks for motocross and cyclocross, and recreational areas along water bodies. Furthermore, linear features of roads and dirt roads were recorded.

Land cover category	Description	Aggregated type of Land cover
Arable land	Arable fields, mosaics of fields, trees and small vineyards, fallow land	Anthropogenic – Agriculture
Permanent grassland	Meadows, pastures, steppes, wetlands	Close to natural
Garden and orchard	Intensive and extensive orchards, large gardens adjacent to built-up areas	Anthropogenic – Agriculture
Vineyard and hop field	Small and large scale, facility included	Anthropogenic – Agriculture
Forest	Forest, non-forest woody vegetation, mountain pine, shrubs, forest nurseries	Close to natural
Water area	Ponds, lakes, reservoirs, pools, flooded mining areas	Excluded
Built-up area	Continuous and dispersed built-up area, industrial, agricultural and military sites, cottages, cemeteries	Anthropogenic – artificial
Recreational area	Garden allotments, spa and sport resorts, zoological gardens, golf courses, campsites	Anthropogenic – artificial
Other area	Mining areas, dump sites	Anthropogenic – artificial

Tab. 2: Land cover categories
Source: Authors' elaboration

Finally, we included anthropogenic structures data in one layer of fragmentation geometry and calculated the index Effective Mesh Size (EMS; Jaeger, 2000; Moser et al., 2007; Girvetz et al., 2008) for all study localities and also for NPs and PLAs for comparison. The input data was composed of fragmentation geometry, a mask of the selected study areas, and a regular square grid (500 × 500 m). Fragmentation geometry was assembled from built-up areas, roads and dirt roads. Fragmentation geometry enters the calculations as a polygon layer; therefore, roads features have been provided with a buffer that expresses their estimated occupation area of land. The radius of the buffer corresponds to the categories of the road network based on the following expert evaluation: motorway – 13 m; first class road – 8 m; second class road – 5 m; third class road – 4 m; maintained dirt or forest road – 3 m; unmaintained dirt or forest road and purpose-built road – 2 m. The expert evaluation was based on an estimate of the average road width of the given category. Two versions of fragmentation geometry (FG) were included in the calculations, namely (FG-a) only built-up areas and roads and (FG-b) built-up areas with roads, dirt and forest roads and purpose-built roads. The result of composing the fragmentation geometry is that we prepared two versions (FG-a and FG-b) for the four mentioned milestones (1950, 1990, 2004, 2020) for our study localities in the Czech Republic.

The EMS method works on the simple mathematic calculations of the size of the areas that remain after cutting out the fragmentation geometry from the layer of interested area. These remaining areas are then intersected with a square grid and the resulting EMS values are calculated according to the formula (Girvetz et al., 2008):

$$m_{\mathrm{eff}}^{\mathrm{CBC}}(\mathrm{j}) = \frac{1}{A_{tj}} \sum_{i=1}^{n} A_{ij} A_{ij}^{cmpl}$$

The resulting variable m_{eff}^{CBC} *(j)* represents the EMS value (calculated in square kilometres) for the given unit (a square 500 × 500 m), where n is the total number of patches extending into one square, A_{tj} is the total area of the square, A_{ij} is the partial area of the patch that extends into the square, and A_{ij}^{cmpl} is the total area of the patch. The values of EMS express in a figurative sense the probability of mutual connection of two randomly located points in the landscape. This means that the higher the value of EMS is, the higher the probability of connecting and, at the same time, the lower the level of landscape fragmentation.

Like in case of land cover, also here the Wilcoxon signed rank, a non-parametric, test in R (R core team, 2023) was used for comparing distribution of anthropogenic structures in selected Natura 2000 sites with average values for all Czech PLAs and NPs and testing the significance of these differences.

4. Results

4.1 Land cover

The six selected localities varied in land cover changes, main processes, and stability as well as anthropogenic pressure. Generally, regardless of protection status (Natura 2000 sites, PLA, NP), all protected areas and studied localities experienced forest area growth, especially those at a higher altitude. The share of stable forest was not significantly different from PLAs or NPs (Tab. 5); however, the share of stable permanent grassland was significantly higher than in PLAs and NPs. Stable arable land was represented less than in PLAs and more than in NPs (Tab. 3). In the Bzenecká Doubrava – Strážnické Pomoraví and Soutok (areas situated in the lowland of South Moravia), intensification of agriculture took place and also the metrics SHDI and ED rose, indicating higher diversity, whereas in other areas both metrics decreased. This was true mainly in Krušné hory Mts. with its large stable forest area, which was enlarged during the study period (Fig. 2). The share of natural and close-to-natural land cover categories was high in all studied Natura 2000 sites and steadily grew, with the exception of the Bzenecká Doubrava – Strážnické Pomoraví and Soutok where the intensification of agricultural use was dominant (Fig. 3).

4.2 Anthropogenic structures and landscape fragmentation

Anthropogenic pressure and the presence of anthropogenic structures are negligible across all areas. Built-up areas were significantly less represented in the selected Natura 2000 sites

Landscape or anthropogenic feature in Natura 2000 localities	PLA	NP	Explanation
Built_up_1960 (less)	**p = 0.016**	**p = 0.031**	In 1960, built-up areas in Natura 2000 study localities were significantly less represented than in PLAs and NPs on average.
Built_up_2016 (less)	**p = 0.016**	**p = 0.016**	In 2016, built-up areas in Natura 2000 study localities were significantly less represented than in PLAs and NPs on average.
Recreation_1960 (less)	**p = 0.017**	**p = 0.045**	In 1960, recreational areas in Natura 2000 study localities were significantly less represented than in PLAs and NPs on average.
Recreation_2016 (less)	p = 0.109	**p = 0.031**	In 2016, recreational areas in Natura 2000 study localities were significantly less represented than in NPs on average.
Roads_1960 (less)	**p = 0.047**	p = 0.344	In 1960, roads in Natura 2000 study localities were significantly less represented than in PLAs on average.
Roads_2016 (less)	**p = 0.031**	p = 0.281	In 2016, roads in Natura 2000 study localities were significantly less represented than in PLAs on average.
Dirt roads_1960 (less)	p = 0.078	p = 0.656	In 1960, dirt roads in Natura 2000 study localities were not significantly less represented than in PLAs and NPs on average.
Dirt roads_2016 (less)	p = 0.219	p = 0.109	In 2016, dirt roads in Natura 2000 study localities were not significantly less represented than in PLAs and NPs on average.
Stable arable land (less)	**p = 0.016**	p = 0.219	Stable arable land during the study period was significantly less represented in Natura 2000 study localities than in PLAs on average.
Stable permanent grassland (greater)	**p = 0.031**	**p = 0.031**	Stable permanent grassland during the study period was significantly more represented in Natura 2000 study localities than in PLAs and NPs on average.
Stable forest (whether differ – less or greater)	p = 1.000	p = 0.063	Stable forest during the study period was not significantly different in Natura 2000 study localities from PLAs and NPs on average.
Stable land cover (whether differ – less or greater)	p = 0.438	**p = 0.031**	Stable land cover during the study period was significantly different in Natura 2000 study localities from NPs on average (NPs are more stable).

Tab. 3: Wilcoxon signed rank test testing significance of difference between selected Natura 2000 sites (n = 6) and PLAs (n = 26) and NPs (n = 4) on average. Selected anthropogenic features were analysed for the beginning (1960) and the end of the period (2016), and landscape features for the whole period (regarding 'stable' land cover and its categories). Testing whether they are less, greater, or testing difference – less or greater (see in brackets). Bold means significant difference
Source: Authors' calculations

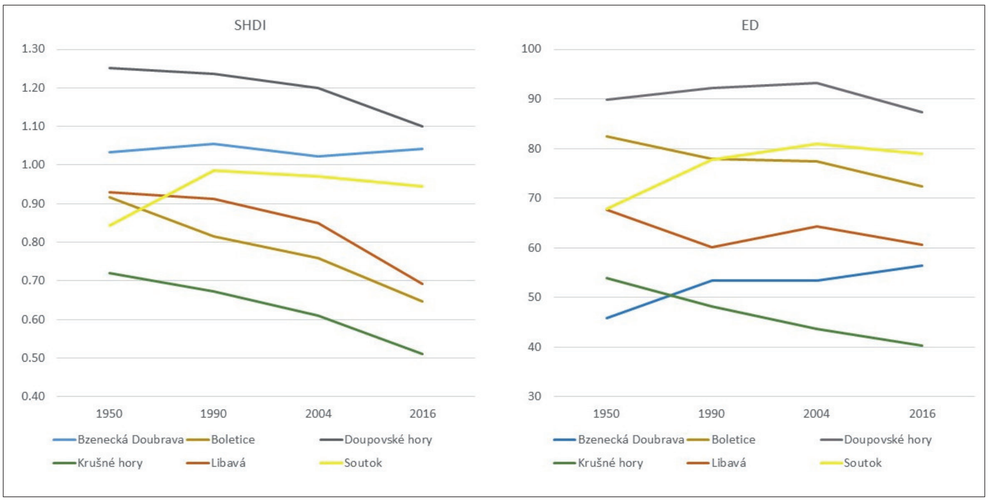

Fig. 2: Development of the selected landscape metrics (Shannon diversity index, edge density) for studied Natura 2000 sites
Source: Authors' calculations

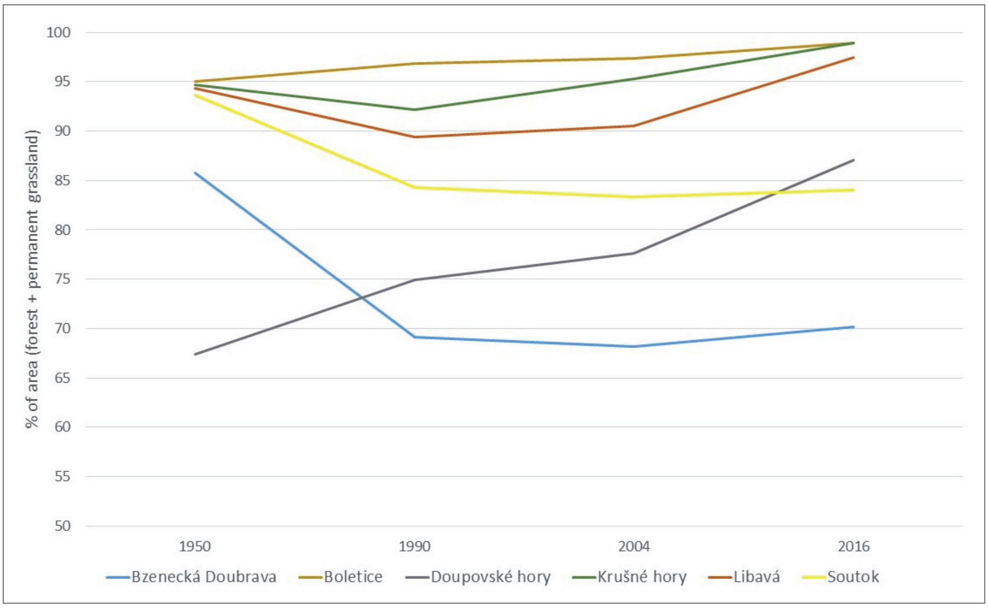

Fig. 3: Share of natural and close-to-natural land cover categories (forest and permanent grassland) in study localities during the study period
Source: Authors' calculations

than in PLAs and NPs. Recreational areas are significantly less represented in Natura 2000 sites than in NPs at the beginning and the end of the study period, whereas in comparison with PLAs, there were significantly less recreational areas in Natura 2000 sites at the beginning and no significant difference is recorded in the most recent period. Road density is significantly lower in Natura 2000 sites than in PLAs and not-significantly but lower than in NPs. There is no significant difference between dirt road density in Natura 2000 sites, NPs, and PLAs (Tab. 3).

The analysis of the level of landscape fragmentation showed that the average EMS values for roads and built-up areas (FG-a) in the Natura 2000 sites were higher by several tens of square kilometres for all years than the average EMS values in NPs and PLAs (Tab. 4.). This significant difference was mainly caused by the different use of the landscape, where three of the six areas of interest have been military training areas with specific landscape management. The average EMS values for built-up areas and roads (FG-a) reached 50.94 km^2 for Natura 2000 sites and 43.98 km^2 for NPs and PLAs at the beginning of the study period (1960). Currently, average EMS values reach 58.76 km^2 for Natura 2000 sites, and 39.95 km^2 for NPs and PLAs. By including dirt and forest roads in the analyses (FG-b), the level of landscape fragmentation will significantly increase to 1.41 km^2 for Natura 2000 sites and 2.01 km^2 for NPs and PLAs (Tab. 4).

4.3 Overview of study localities

There are some differences and similarities between the studied Natura 2000 sites. We point out the most significant features in more detail below (see Tab. 5 and Tab. 6):

Fragmentation geometry	Protected areas	1960	1990	2004	2016
FG-a	Natura 2000	50.94	83.08	61.17	58.76
	NPs/PLAs	43.98	41.50	43.82	39.95
FG-b	Natura 2000	2.54	2.59	1.97	1.41
	NPs/PLAs	3.36	2.04	1.90	2.01

Tab. 4: The average EMS values for roads and built-up areas (FG-a) and built-up areas with roads, dirt and forest roads and purpose-built roads (FG-b) in Natura 2000 sites and NPs/PLAs during selected time milestones
Source: Authors' calculations

- Bzenecká Doubrava – Strážnické Pomoraví experienced intensification of agricultural use and urbanisation, especially before 1990; thus, arable land (from 12% to 26%) and built-up areas grew, whereas permanent grassland declined rapidly from 29% to 9%. Afforestation also took place with an increase in forest from 57% to 61%. Landscape structure stayed relatively diverse, with an increasing number of patches and edge density. Land cover was stable at 66% of the area during the study period, with stable forest being the main part of the area. The rate of built-up area growth is the largest in comparison with other areas (from 0.4% to 1.3%). Also, road density increased slightly, whereas dirt road density decreased. This area also has the largest share of recreational areas in comparison with other study localities. The average value of EMS (FG-a) decreased from 64.04 km^2 in 1950 to 54.52 km^2 in 2016 (Fig. 4). On the other hand, the average value of EMS with dirt and forest roads (FG-b) gradually increased from 1.54 km^2 to 2.1 km^2.
- Change in another Natura 2000 site – Boletice – could be defined as afforestation; arable land almost vanished (from 3%) and permanent grassland decreased (53% to 27%), resulting in forest increase from 42% to 72%. Therefore, permanent grassland together with forest created the vast majority of the area. Landscape structure was unified and land cover remained stable at 61% of the area. The area is almost without anthropogenic structures with an increase in small built-up areas, while road and dirt road density shrank. Recreation areas were presented only negligibly. For the EMS, we observed a significant increase from 109.4 km^2 to 145.1 km^2 in 2016 (Fig. 4), reducing the fragmentation rate by almost 50%. For forest and dirt roads, this increase was only slight (from 1.41 to 1.68 km^2).
- Doupovské hory Mts. was, during the whole period, covered largely by permanent grassland, which ranged from 30% to 40% with a decrease from 40% to 36%. Afforestation caused a growth of forest from 27% to 51%. Arable land shrank from 28% to 9%. The area went through a large change as only half of the area retained the same land cover with unifying of landscape structure occurring especially in the central and western part of the area, where forest covered the former landscape mosaic of meadows, fields, forests, and settlements. The area had the largest portion of built-up areas; despite the decrease before 1990, it grew from 1.5% to 1.8%. Roads and dirt roads were slightly shortened. Recreational areas continuously increased but only covered a negligible area. Due to the increase in anthropogenic structures, especially on the edges of the study locality, the average value of EMS (FG-a) decreased from 53.12 km^2 to 45.16 km^2 and this led to an increase in the degree of landscape fragmentation. In the case of forest and field roads (FG-b), the EMS value dropped from 2.41 to 1.57 km^2.
- Krušné hory Mts. was predominantly forested and characterised with ongoing forest area growth (from 76% to 83%). Arable land grew from 4% to 7% between 1950s and 1990s and then almost vanished from the study locality. The landscape is stable (land cover remained stable on 82% of the area) but experienced homogenisation of landscape structure. Built-up areas increased slightly, especially after 1990. Roads were reduced, whereas dirt road density increased. Recreational areas were newly developed, which was in particular caused by the construction of ski slopes. The degree of landscape fragmentation by built-up areas and roads stagnated, and in 2016 the average EMS value was 12.8 km^2. In the case of forest and dirt roads, the value of EMS decreased to 0.88 km^2, and thus there was an increase in the degree of landscape fragmentation.
- Libavá mainly experienced afforestation, with forest area growth from 50% to 73%. Permanent grassland (45% to 24%) and arable land (4% to 2%) generally decreased during the whole period, but an increase from the 1950s to 1990 was

Study localities	Main changes of selected land cover categories areas during the study period (%)						Stable land cover (%)			
	1950 – arable land	2016 – arable land	1950 – permanent grassland	2016 – permanent grassland	1950 – forest	2016 – forest	stable arable land	stable permanent grassland	stable forest	overall stability of land cover
Bzenecká Doubrava – Strážnické Pomoraví	12.23	26.16	28.80	9.32	56.98	60.82	7.07	5.00	53.43	66.34
Boletice	2.74	0.03	52.70	26.52	42.30	72.37	0.00	20.41	40.70	61.46
Doupovské hory Mts.	28.48	8.92	40.11	36.49	27.32	50.57	6.93	16.51	25.21	50.17
Krušné hory Mts.	4.10	0.01	18.76	16.2	75.92	82.73	0.00	7.03	74.27	81.50
Libavá	3.68	1.58	44.63	24.4	49.70	73.07	0.28	13.34	48.39	62.26
Soutok	5.82	13.63	29.22	16.54	64.39	67.46	4.15	9.82	56.66	71.03
Czech NPs	7.85	1.76	19.76	15.95	70.08	79.13	1.32	8.75	68.44	79.75
Czech PLAs	24.79	9.70	17.01	21.78	53.67	61.30	7.71	5.98	51.86	68.51

Tab. 5: Overview of study localities with the most important studied land cover features and comparison with NP and PLA
Data source: Authors' calculations

Study localities	Built-up areas (%)				Recreational areas (%)				Roads (km/km^2)				Dirt roads (km/km^2)			
	1960	1990	2004	2016	1960	1990	2004	2016	1960	1990	2004	2016	1950	1990	2004	2016
Bzenecká Doubrava – Strážnické Pomoraví	0.36	0.75	1.05	1.31	0.01	0.18	0.38	0.39	0.13	0.13	0.14	0.15	4.44	4.35	4.10	4.05
Boletice	0.34	0.58	0.58	0.56	0.00	0.00	0.01	0.00	0.34	0.45	0.38	0.29	5.19	3.40	3.61	3.96
Doupovské hory Mts.	1.48	1.43	1.63	1.81	0.01	0.02	0.03	0.03	0.70	0.63	0.65	0.65	3.35	3.02	3.13	3.30
Krušné hory Mts.	0.37	0.40	0.45	0.54	0.00	0.03	0.06	0.07	0.49	0.48	0.42	0.42	4.29	4.51	4.57	4.71
Libavá	0.69	0.59	0.57	0.54	0.00	0.00	0.00	0.00	0.44	0.31	0.38	0.38	5.09	4.04	3.85	4.21
Soutok	0.16	0.27	0.41	0.39	0.00	0.03	0.02	0.05	0.13	0.17	0.16	0.19	3.20	3.45	2.98	3.38
Czech NPs	1.01	1.34	1.52	1.64	0.01	0.25	0.36	0.45	0.41	0.44	0.42	0.40	4.20	4.10	4.04	4.24
Czech PLAs	2.50	3.32	3.57	3.89	0.02	0.08	0.15	0.19	0.58	0.61	0.60	0.60	4.85	4.20	4.18	4.10

Tab. 6: Overview of study localities with the studied anthropogenic features and comparison with NP and PLA
Data source: Authors' calculations

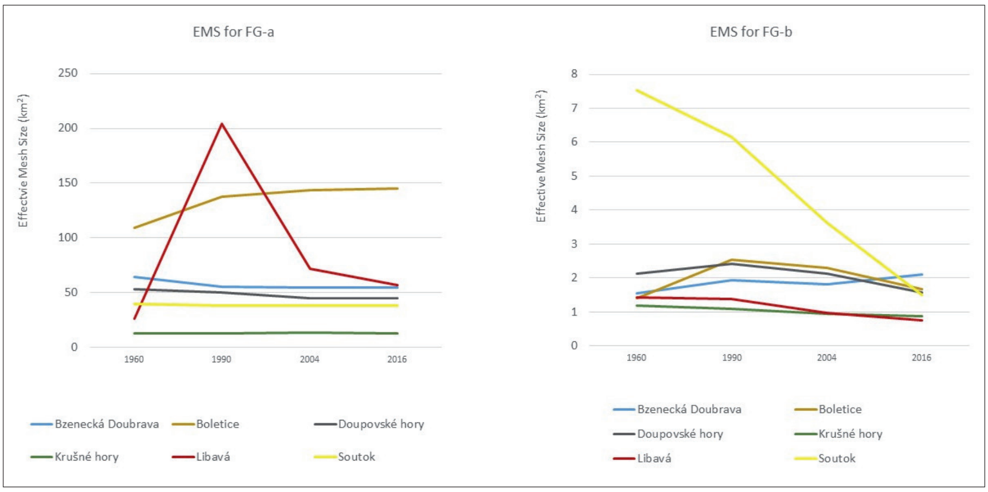

Fig. 4: Development of average Effective Mesh Size for the studied Natura 2000 including built-up areas and roads (FG-a) and built-up areas, roads, dirt and forest roads, and purpose-built roads (FG-b)
Source: Authors' calculations

recorded. Landscape structure was unified and land cover remained stable at 62% of the total area. Built-up areas slightly declined. Roads and dirt roads were shortened. Recreation was barely present in the area. The average value of EMS (FG-a) increased significantly from 26.51 km^2 to 56.78 km^2 during the monitored period. A massive increase in the EMS value was recorded in 1990 due to the missing part of the road section in the road network (Fig. 4). In contrast, the average value of EMS (FG-b) halved from 1.43 km^2 to 0.75 km^2 in 2016.

- Soutok was affected by agricultural intensification, with a growth of arable land from 6% to 14%, especially before 1990, whereas permanent grassland declined from 29% to 17%. Forest increased slightly from 64% to 67%. Landscape increased its diversity with the stable forest area and overall stability of 71% of the total area. Built-up areas had the smallest share among all studied localities, but they grew. Roads and dirt roads enlarged their network. Recreation areas emerged from the garden allotments. The average value of EMS (FG-a) decreased only slightly from 39.57 km^2 to 38.23 km^2. A significant decrease in the average value of EMS was observed in the case of forest and dirt roads (FG-b), from 7.53 km^2 to 1.51 km^2 in 2016 (Fig. 4).

5. Discussion

As our results show, selected areas protected as Natura 2000 sites can, from the landscape perspective, be regarded as valuable parts of the Czech landscape without significant presence of anthropogenic structures and with the prevalence of natural or close-to-natural land cover categories. This fact confirms their uniqueness and justification for inclusion in the Natura 2000 network, but also for national designations, at least as PLAs. If done so, they would contribute to fulfilling improvement of the conservation status to reach 30% of sufficiently protected areas (European Commission, 2021). This is also stressed because the selected Natura 2000 sites more or less overlap the "Biotope of selected specially protected large mammal species", a GIS layer delimiting key parts of the Czech Republic for functional landscape connectivity, which creates obligatory data for spatial planning (Hlaváč et al., 2021). Furthermore, low fragmented large PAs are of high ecological quality because they accommodate species movement and, at the same time, boost climate change resilience (Lawrence & Beierkuhnlein, 2023).

The majority of the selected Natura 2000 sites are located in the peripheral regions of the Czech Republic, with specific landscape development. Also, Jepsen et al. (2015) mention that drivers and the timing of these changes are identical for wider area of the former Soviet bloc of European countries. Our study localities experienced relatively large land cover change (except Krušné hory Mts.) in accordance with other EU Natura 2000 sites (Guerra et al., 2019; Hermoso et al., 2018). In our study localities it was caused in particular by ongoing abandonment and extensification of land use (Feranec et al., 2010; Kupková & Bičík, 2016); for example, afforestation is present in all study localities, which is a trend common for PAs across Europe (Ameztegui et al., 2021; Žoncová, 2020).

Our hypothesis regarding higher anthropogenic impact (urbanisation and land use intensification) occurring in the Natura 2000 sites across Europe (e.g. Mammides et al., 2024) was not confirmed and only partly concerned two smaller, lowland localities (Bzenecká Doubrava – Strážnické Pomoraví and Soutok). Both sites are threatened in particular by agricultural intensification as suitable areas for agriculture (Kupková & Bičík, 2016; Kupková et al., 2021) and by unsuitable management of valuable forests (Miklín & Čížek, 2014). These findings are in accordance with results from the studies by Hermoso et al. (2018) and by Concepción (2021).

It should be stressed that by using our data and analyses, we were not able to characterise the ecological quality of the habitats or ecosystems, only land cover categories and their dynamics. However, we evaluated stability and the share of natural and close-to-natural land cover categories as a proxy of quality (Guerra et al., 2019). In this manner, despite detecting relatively large changes, these changes were predominantly represented by increasing share of natural and close-to-natural land cover categories (Fig. 3), leading to the presumption of increased ecological quality of habitats. However, recent study showed that Czech Natura 2000 sites protect sufficiently mainly critically endangered habitats but not natural habitats in general (Pechanec et al., 2018).

Increase in the share of natural and close-to-natural land cover categories are mainly result of landscape abandonment, especially in steeper (and more remote) regions, and general simplification of landscape structure. This was not only in the last two decades or so, as found by Hermoso et al. (2018), but these processes started even as early as the 1950s (Figs. 2 and 3) and were recorded also elsewhere (Lasanta et al., 2017). All mountainous Natura 2000 sites were affected by the expulsion of Czech Germans after World War II, leading to depopulation and afforestation (Janík et al., 2022), and these landscapes are now still relatively abandoned, as also stated by Mareš et al. (2013).

Boletice, Doupovské hory Mts., and Libavá have similar landscape trajectories and drivers. These localities overlap significantly with military training areas, which were established on previously inhabited areas with a large share of open landscape (Skokanová et al., 2017; Havlíček et al., 2018). Logically, the typical development of built-up areas and road networks could not occur here, as happened in the normally accessible countryside, but current land cover composition and biodiversity could be positively influenced by the former military management (Svenningsen et al., 2019). Landscape abandonment caused growth of forest area in particular and a significant decrease in the area of permanent grassland. However, this land cover type was maintained in some parts with military activities (Havlíček et al., 2018; Janík et al., 2022; Lipský et al., 2022). Similar changes were also detected elsewhere across Europe, especially in peripheral and mountainous regions (Feranec et al., 2010; Fuchs et al., 2013). Many authors point out wilderness and high biodiversity in military training areas. Parts of these areas were transferred into the Natura 2000 network or into national networks of protected areas because of their high conservation values (Seidl & Chromý, 2010; Schumacher & Johst, 2015; Ellwanger & Reiter, 2019). To preserve biodiversity, it is necessary to manage landscape structure, which is on the decline and is now maintained as a side effect of military activities. Specific restoration and management measures need to be implemented in order to maintain endangered habitats, for example against succession, which is often a major problem (Šíbl & Klimová, 2011). Moreover, the current situation regarding Russian invasion of Ukraine has led to an increased focus on national defence and we are unlikely to see the transformation of military training areas into nature PAs in the foreseeable future.

Krušné hory Mts., on the other hand, has been a predominantly forested mountainous area with high stability of land cover and low human presence (Janík et al., 2020), with similar landscape features as other already protected mountain ridges across the Czech Republic (e. g. Český les, Jizerské hory, Jeseníky). However, the mountains were previously inhabited by the mining industry (Bastian, 2013; Janík et al., 2022). The increase in the forest landscape category that we found coincides with the results of Palmero-Iniesta et al. (2020) who showed that afforestation related with forest patch coalescence occurs in European forested areas. The high conservation value of Krušné hory Mts. has also been documented by Bastian et al. (2010) and Bastian (2013). They also suggest appropriate management of habitats and ecosystems in order to maintain biodiversity and the ecosystem services that they provide as well as to create job opportunities by implementing management plans.

National designation of all the studied Natura 2000 sites in this article (or even with their surroundings) could strengthen the connectivity of the Czech landscape between current PLAs and NPs: Boletice would connect Šumava PLA with Blanský Forest PLA; Doupovské hory Mts. and Krušné hory Mts. are situated between Slavkov Forest PLA and Labské pískovce LPA; Bzenecká Doubrava – Strážnické Pomoraví and Soutok are located between Bílé Karpaty PLA; and Pálava PLA and Libavá would fill the gap between Litovelské Pomoraví PLA and Poodří PLA (see Fig. 1). Moreover, the majority of the study localities are less fragmented (by roads and built-up areas) than the rest of Czech Republic (Romportl, 2017). On the other hand, landscape fragmentation by dirt and forest roads is relatively high in Natura 2000 sites. However, dirt and forest roads, which we included in the analyses, have different effects on landscape functions and it is necessary to evaluate them individually (Zielińska, 2007; Lindenmayer, 2018). Further protection of critical points outside the areas would be necessary, but national designation with appropriate management of these relatively natural areas with minimum human presence could enhance landscape functional connectivity (Hlaváč et al., 2021).

Doupovské hory Mts., Soutok, and Krušné hory Mts. have been discussed for national designation as PLAs for a long time (Pelc, 2018). While the process of declaring Soutok as PLA has been completed and the declaration of Krušné hory as PLA has been initiated, discussed in depth with local, stakeholders, and could be seen as being finalised in the coming years, declaration of Doupovské hory Mts. as a PLA is rather academic due to its strategic role in military training (NCA, 2023).

6. Conclusion

Selected localities within Natura 2000 sites are valuable for preserving ecological stability and connectivity from a landscape point of view. They are less affected by anthropogenic pressure than other Czech PLAs and NPs and also than Natura 2000 sites across Europe. The study localities are predominantly covered by natural and close-to-natural land cover categories – they are largely forested or covered by permanent grassland with significant cultural and natural heritage – and the share of these categories have increased in the majority of the localities.

Therefore, national designation of these areas as protected landscape areas (or even national parks) could prevent them from intensification of land use, help to set suitable management and, via these steps, secure landscape connectivity between already protected areas and contribute to the better coherence and functionality of the Czech PA network.

The further research steps will focus on the comparison of PAs and their surroundings in terms of land cover and anthropogenic pressure changes and development. Moreover, connectivity and conservation priorities will be analysed in the PAs and their surroundings for landscape planning addressing the issues of nature conservation.

Data are visible on website: https://experience.arcgis.com/experience/b948109ec019412882a4734c8303bbce/.

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Assessing the cultural heritage of historical ferries: A case study from the Czech Republic

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Abstract

The aim of the article was to evaluate the importance of historical ferries and ferry ports from the point of view of cultural heritage. The research took place in two model areas in the lands of Bohemia and Moravia in the Czech Republic. The registered transfer points supplemented by supporting database from historical topographical maps can be an appropriate basis for assessing the importance of cultural heritage. A follow-up archival and field research made it possible to objectively assess the potential of river ferries for cultural heritage. The knowledge and information about historical river ferries can be objectively used to make places more attractive for tourists. An ideal form of preservation of the cultural heritage is represented by preserved objects connected with the operation of the ferry, and the remains of anthropogenic landforms and landscaping. The construction or restoration of some objects associated with ferry operations contributes to the preservation of cultural heritage in this specific area of transport. The article attempted to verify whether the proposed methodology for assessing the cultural and historical values of river ferries is a suitable tool for assessing the importance of individual river ferries as a cultural heritage.

Keywords: River ferry, cultural heritage, archival research, Czech Republic, tourism

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1. Introduction

Large watercourses embody a landscape feature that often defines the natural administrative boundary between different regions (Popelka & Smith, 2020; Haselsberger, 2014). Similarly, major rivers also form a physical obstacle, being a significant barrier to transport corridors. Finding suitable means to move across such watercourses is therefore a principal challenge in the designing of transport routes. The past road network systems are frequently targeted by specialized history and microhistory researchers, who utilize preserved written and graphical sources, maps in particular (Tomeček, 2000; Ortiz, 2021; Vletter & Spek, 2021). River ferries, a broadly preferred crossing option, were popular especially in the middle and lower reaches, where establishing a permanent fixed link between the banks embodied an excessively difficult or even unfeasible task (Junxiang, 2020; Doswald, 2019).

From the Middle Ages into the modern times, the ferries allowed, above all, transporting cargo and goods along longer trade routes, in sectors unfavorable for fording (Martínek et al., 2014), and – using water-powered structures, too – facilitated supplying diverse products to those segments of the population that worked in the dynamic domains of food processing and craft manufacturing (Lucas, 2005). Stone bridges existed only in larger settlements before the mid-19th century; more common were wooden bridging structures, but these exhibited a limited material life cycle (Kromoser et al., 2023; Singh & Page, 2018). Further, bridges in general were highly vulnerable to natural hazards such as floods and earthquakes (Argyroudis & Mitoulis, 2021). When under reconstruction and renewal, bridges were regularly substituted with ferries (Parry, 2021). In the Middle Ages, the paid operation of ferries was originally a part of the privileges enjoyed by the superior authorities. The privileges also included collecting tolls to maintain the road, bridge, or ferry grounds (Ivanič & Husár, 2019); in reality, however, only a portion of the toll was employed for this purpose, most of the money being transferred to the king or used to satisfy the needs of the superior collectors (Vangel & Decký, 2010; Ivanič, 2019). In 1870, the Water Law for the Kingdom of Bohemia was passed, rendering the ferry business a licensed commercial activity (Čížek, 1886).

In what now is the Czech Republic, a total of 514 river ferry sites were identified on the basis of systematic registration, using old topographic maps from four time periods between 1763 and 2020; this amount gradually increased to 542 after other archival sources had been studied (Dostál et al., 2021). The ferries reached a peak during the 19th century, their overall quantity and distribution reflecting the dramatically increased demands on the transport system; this trend had arisen from the denser and faster flow of goods and people, an effect accompanying the Industrial Revolution (Derry & Williams, 1993; Bogart, 2013). The continuously increasing volumes of traffic, together with requirements for its broad acceleration, resulted in the ferries being progressively replaced in the 20th century with robust bridges made of iron, steel, concrete, reinforced concrete, and stone.

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Small river ferries are a rediscovered mode of travel in several countries, enhancing and bringing new dimensions to tourist landscape traveling experiences. The river crossing provides an experience of being on water, and the material structure of the ferry grounds significantly shapes on-board interactions whilst providing new perspectives of place (McGrath et al., 2020). Currently, ferries in the Czech Republic are operated mainly in areas with a recreational function, and they usually involve motor boats, often on new water reservoirs. The classic transport purposes have been preserved in a few ferries on the Labe and the Berounka rivers and the Lipno reservoir. In multiple cities worldwide (Prague, for example), ferries have become an integral part of public transport (Bignon & Pojani, 2018; Cheemakurthy et al., 2017), thus not only preserving a certain tradition in the transport system but also conveniently reducing the daily commuting time, in addition to being a tourist attraction. Tourist demand, by extension, embodies a driving force that can lead to the preservation of this form of transport (Tarkowski et al., 2021; McGrath et al., 2020).

Transport-related technical attractions, monuments, and sites of cultural heritage are not only a focus of interest for industrial heritage experts (Gagliardi et al., 2022; Molina-Castaño et al., 2023) but also form popular, charming destinations for tourists and transport enthusiasts (Rovelli et al., 2020). At the same time, traditional, historical modes of transport deserve protection and cautious use (Smrčka, 2021). The cultural and historical potential for tourism is nevertheless not restricted to urban settlements or major regional places of historical interest, as rural locations often feature unique architectures too (Pascu & Pătru-Stupariu, 2021). Historically, river ferries were operated mainly in smaller villages; in large cities, by contrast, high-quality stone or brick bridges prevailed, having been built by the nobility or townspeople.

Cultural heritage plays a prominent role in reshaping cities' current morphologies, reinforcing public sense of belonging, cultural identity, and place authenticity (Fouad & Sharaf Eldin, 2021). The most important parameters characterizing cultural heritage are historical space and historical time (Lauzikas, 2005). The exact spots and continuity of the river ferries can be derived partly from old topographic maps (Timár et al., 2006; Janata & Cajthaml, 2021) and, in the same manner, from archival data (Dostál et al., 2021). Simultaneously, however, from the perspective of cultural heritage, it is essential to investigate the traces of defunct ferries, especially as regards the surviving supplementary buildings (the ferryman's house, traveller's inns, boarding areas), typical river bank topographies and shapes, remnants of adjacent roads, and local names (Havlíček & Dostál, 2020). In addition to the cultural and historical values, the tourism potential of such defunct sites should be examined too (Dostál & Havlíček, 2021).

The aim of the paper is to evaluate the importance of historical ferries and ferry ports in terms of the cultural heritage in the Czech Republic. The relevant research questions have been defined as follows:

- Are the registered ferry sites, completed with a supporting database from old topographic maps, a suitable basis for assessing the importance of cultural heritage?
- Is the proposed methodology for assessing the significance of cultural and historical values of river ferries a suitable tool for assessing the significance of individual river ferries?
- Is the historical and functional aspect of individual ferry sites the key to the degree of preservation and authenticity to the present day?
- Is the knowledge and information about historic river ferries, in whole or in part, applicable in making the sites more attractive for tourism?

2. Theoretical background

2.1 Historical importance of river ferries for transport system

Ferry, a place where passengers, freight, or vehicles are carried by boat across a river, lake, arm of the sea, or other body of water. The term applies both to the place where the crossing is made and to the boat used for the purpose (Britannica, 2024). Perhaps the most prominent early use of the term appears in Greek mythology, where Charon the ferryman carried the souls of the dead across the River Styx. Ferries were of great importance in ancient and medieval history, and their importance has persisted into the modern era (Britannica, 2024). River ferries have been used for transport across waterways since the regular transport of goods and people, while the first systematic mentions of ferry operations are linked to old trade routes (Martínek et al., 2014). Direct evidence of the operation of ferries on large rivers is documented in the first historical documents and deeds from around 1100 AD and 1200 AD, for example from monasteries, manors, towns, villages and around castles (Redwood, 1994; Kröger, 2018; Kröger, 2023).

2.2 Options of mapping ferries

Until the 18th century, the existence and localization of ferries in the area of Central Europe was mainly linked to verbal descriptions from archival documents (Kröger, 2018). In the case of localization near settlements, it was possible to interpolate the location of the ferry in relation to the structure of the settlement, e.g. city gates, important historical buildings, in the open countryside outside the settlements, the localization of river ferries is more difficult. The use of topographic maps, which were created in Europe in the 18th century, is essential for more accurate localization of ferries (Timár et al., 2006). From these mostly military maps, it is possible to obtain a more comprehensive picture of the number and distribution of river ferries in the landscape (Dostál et al., 2021). However, even these maps from the 18th century do not yet reach the accuracy that can be used for the unambiguous localization of objects today (Janata & Cajthaml, 2021). Since the middle of the 19th century, positionally accurate maps, which are based on geodetic foundations, have gradually become available in Central Europe (Ostafin et al., 2021). Complex mapping of ferries is possible with the use of several sets of old topographical maps, while their applicability in Central Europe is suitable for the period from the middle of the 18th century to the middle of the 20th century (Dostál et al., 2021).

2.3 Cultural-historical and transport research on ferries

Compared to the research of historical bridges, road routes and other transport objects, the research of historical river ferries is a relatively marginal matter. It is research at the border of several scientific disciplines, where the interests of historians, archaeologists, geographers, and transport experts meet (Redwood, 1994; Junxiang, 2020; Doswald, 2019; Dostál et al., 2021; Kröger, 2023). From the point of view of the development of transport and trade, historically, river ferries played a similarly significant role, as the first emerging bridges (Kromoser et al., 2023; Singh & Page, 2018). Transport-related cultural heritage sites are the focus of industrial heritage experts (Gagliardi et al., 2022; Molina-Castaño et al., 2023). Remains of river ferry operations, preserved technical objects on the banks of rivers, buildings of ferry operators, specific information published in the location of the ferry can also be included among important cultural heritage, at the same time they have potential for the development of tourism (Dostál & Havlíček, 2021). In several cities in the world, ferries have become part of public transport, thus continuing the tradition of historical ferries on large and medium-sized rivers (Bignon & Pojani, 2018; Cheemakurthy et al., 2017). Tourist demand embodies the driving force that can lead to the preservation of this form of transport (Tarkowski et al., 2021).

3. Methods and data

3.1 Evaluating the cultural and historical importance

The methodological approach to the evaluation of the cultural and historical aspects of river ferry grounds arises partially from the methodological procedures for evaluating and protecting the Czech Republic's industrial heritage (Ryšková et al., 2022; Matěj & Ryšková, 2018) and, also to a certain extent, exploits the techniques that allow the classification and evaluation of industrial heritage from the perspective of heritage conservation centered on water management facilities. Technological monuments and industrial heritage are evaluated via traditionally conceived art historical, architectural, and urban planning criteria, taking on specific degrees of authenticity or historical context. The criteria include the typology value, integrity of the technical equipment, and traces of operation. To evaluate the industrial heritage in relation to water management, the methodology applied in the Czech Republic comprised the following value types: typology, technical flow, system link, authenticity, architectural, art historical, landscape/urban, and age. Besides specific items (such as, in ferry sites, the actual means of cross-river transport, being a raft or a boat), entire functional units are assessable too: the guide ropes, piers, boarding point stairs or steps, road sectors leading down to the river, anchoring elements on the banks, information signs, maps of the area, system to call in the ferryman, passenger facilities, ferryman's house, traveller's inn or restaurant, and other associated objects.

For the purposes of assessing the cultural and historical importance of ferries, we propose a methodology to assess/calculate the below specified criteria.

A) Typology value

Applying this criterion requires knowing the typological development of the relevant objects, including major milestones, typical representatives, and uniqueness of the object. The exclusivity of a building in a local, regional, or international context rests on one or more of the following preconditions: the first, oldest surviving, or only preserved of its type; exceptional structural and technological parameters; and exclusive structural design. A typical representative (relating to a class of buildings) carries the characteristics of the type, is in a well-maintained state, and the technology has remained functional. This criterion applies to both the functional unit (such as an operative ferry for transporting vehicles) and a part of that unit (for instance, a surviving ferryman's house). When evaluating the typological values of ferries, it was taken into account how representative it was within its category (large ferries, ferries, boats), or what was the uniqueness of the technical solution of the ferry itself, the boarding place for passengers and cargo, the surroundings, or the synergistic connection with subsequent functions (for example the use of ferries at water mills). Values 0 to 3.

B) Technological flow value

Technological flow is related to the functionality of the whole. The object under assessment may already be integrated in a larger functional unit that involves the flow of energy or material in a general sense; in the case of ferries, the central process is embodied in the specific transport of people, goods, and materials. An interesting issue may therefore lie in the actual demand and supply for the realization of a transport route or trip, which may have changed markedly throughout history (for instance, some of the ferries to haul materials to industrial plants were possibly later used to transport people). The technological flow value is assessed in the vicinity of the object of transport, at a distance measured in kilometers. The importance of the technological flow was taken into account according to the potential of transported people and cargo in the past, based on available statistics, historical data, photographs, the potential of the number of inhabitants in the hinterland of the ferries, local spatial connections were also taken into account, in particular the connection of agricultural farms and yards in history, including manor houses. The value of the technological flow can be increased based on proven involvement in production chains. Values 0 to 3.

C) System links value

A technological unit in a broader context, with an overlap to other sectors of industry, transport, and energy; in ferry grounds, the value is applicable to the importance of the ferry within the entire set of transport links, involving ferries on major regional or international roads, the connection of a ferry to a significant railroad route, and other similar factors. Primarily, the link to functional inclusion in the road network is evaluated here (Values: 3 = imperial road; 2 = other roads; 1 = local road; 0 = local transport link), connection to railway stations and stops in the immediate vicinity. Furthermore, knowledge about the connection of important industrial enterprises in the region, the connection of important administrative and cultural centers of the region is also important for system links. Values 0 to 3.

D) Authenticity value

This criterion is an expression of the degree of originality in several aspects and includes various subcategories. The authenticity of function: determines whether the ferry and accompanying buildings serve their initial purpose and are operational. The authenticity of technical installations: based on an assessment of the survival of the original installation or of certain functional elements of the buildings. The authenticity of form: compares the current and the original states of the building or its parts, considering the form of the buildings within the initial architectural or technical design. The authenticity of matter: determines the stage of preservation in some of the original materials employed to construct the ferry site, such as those on the surface of the river access road or in the structure of the ferryman's house. By extension, we may include also the degree of conservation that characterizes some of the geomorphological formations modelled to suit the ferry site; these formations comprised, above all, the river bays where the water flow was moderate enough to allow embarkation and disembarkation. The value of authenticity was evaluated on a scale of 0 to 3, i.e. 0 = none, very weak, 1 = low, 2 = medium, 3 = high. Any form of authenticity (function, form, technology) was taken into account. For this evaluation, the current state of the objects in the location of the ferry or in the immediate vicinity is crucial, in the absence of any trace of the existence of the ferry, a value of 0 was assigned. Values 0 to 3.

E) Architectural value

A traditional principle for the assessment of the heritage impact. The aspects taken into account involve whether the building represents a particular style, movement, or period, and whether a well-known architect participated in the construction. Regarding ferry sites, the criterion is mostly applied to complementary buildings (including, but not limited to, inns and ferryman's houses). The architectural value was evaluated on a scale of 0 to 3, i.e. 0 = none, very weak, 1 = low, 2 = medium, 3 = high. The value 0 was applied in locations where no trace of the existence of the ferry has been preserved to date and no buildings associated with the operation of the ferry can be found in the vicinity. The architectural value was evaluated for preserved buildings connected to the operation of the ferry: ferryman's house, inn, mill, warehouses or technical buildings, etc.). Values 0 to 3.

F) Art historical value

The subcategory covers the arts and crafts-related elements (ironwork and ironmongery, fittings, artistically crafted railings, and other similar components) and artistic details (for instance, special plaster, tiles, or mosaics) or products. In the case of ferry sites, relevant items, such as monuments and plaques, are usually found on the complementary buildings or in the vicinity of the premises. The art historical value was evaluated on a scale of 0 to 3, i.e. 0 = none, very weak, 1 = low, 2 = medium, 3 = high. A value of 0 was given in locations where no trace of the ferry's existence has been preserved to this day. Lower art-historical values were assigned in locations where monuments, information signs or other reminders of the ferry are preserved. Higher values were assigned in locations with preserved buildings or accompanying technical elements. Values 0 to 3.

G) Landscape value

This value includes the impact of the building on the landscape or settlement, establishing whether the building fits in and how it affects the landscape. The factors of focus are the visual dominance, place identity, and role of a landscape-forming element and its stage of integration into the environment. The visual landscape value of the place and locality was perceived as the influence of the locality on the landscape character during the evaluation of the ferries. This value was scored on a scale of 1 to 3, i.e. 1 = low, 2 = medium, 3 = high. The value 0 corresponded to the absence of landscape value, it was primarily a case of localities where there is no longer any continuity with the original occurrence of the ferry at the watercourse, because this watercourse was moved elsewhere after regulation. Locations near regulated watercourses, locks, and densely built-up areas showed very low landscape values. Higher landscape values were recorded for locations with bays, with preserved entrances to the water, accompanying buildings, historic trees, avenues, historic buildings and naturally valuable surroundings. Values 0 to 3.

H) Historical value

The subset covers a wide range of parameters, depending on the context; the relevant factors then comprise local history, the evolution of a particular industry or craft, and links to cultural, literary, and art histories (as exemplified by landscape painting or photography). Some ferries and their surroundings could in the past have been the subject of works by painters, writers, or other artists. When evaluating the historical importance of the ferry, its importance for local industry or the development of some parts of cities and towns was also taken into account (e.g. the link to the development of recreation in the form of tramp settlements). The historical value was evaluated on a scale of 0 to 3, i.e. 0 = none, very weak, 1 = low, 2 = medium, 3 = high. A value of 0 was given to ferries that were operated in the recent past and thus have no major historical significance. Values 0 to 3.

I) Age value

This value was derived from the time the ferry was in service with an emphasis on older periods and long-lasting continuity. Ferries operated for only a few units or decades in the 20th or 21st century have lower or zero value. Ferries with historical use since the Middle Ages or from the 18th and 19th centuries have higher values. The highest values of continuity are achieved by continuously used ferries with operation until the present day, or with long-term operation until the second half of the 20th century. Values 0 to 3.

For the overall evaluation of the importance of a specific ferry in the historical context, the strongest connection to the surroundings, the greatest importance in terms of the connection of roads, villages, settlements, industry, and the greatest importance regarding the type of transport object were always evaluated. Therefore, the highest value was always taken into account during the entire evaluated period. As an example of the dynamics of the development of the ferry and the reduction of its significance, the following can be cited: a historically significant connection of traffic with the use of a large ferry with a regional overlap, later a decrease in significance due to the construction of a bridge in the nearby area, in another period the use of a small boat to connect the village with a holiday cottage settlement. In this case, the highest importance in the historical development of the site was taken into account. For each location of the ferry, a value of 0 to 3 for all nine criteria of cultural and historical significance was added expertly by the research team. The total value of the cultural-historical significance of the ferry could thus potentially range from a minimum of 0 to a maximum of 27. Comparison of the significance of the ferries in the two model territories was made possible by comparing the average values and other statistic values both for the overall point assessment and for individual types of cultural-historical values.

3.2 Methodology for mapping ferry sites using historical topographic maps

The mapping of historical ferry sites exploited, above all, historical topographic maps produced through the following surveys:

i. 1st Austrian Military Survey (1:28,800) of 1763–1768,
ii. 2nd Austrian Military Survey (1:28,800) of 1836–1852,
iii. 3rd Austrian Military Survey (1:25,000) of 1874–1880,
iv. Czechoslovak military mapping (1:25,000) of 1952–1956.

All the topographic maps of the Czech Republic were available in an electronic version of the original scans, in a georeferenced form usable for operating with geographical information systems. In addition to the georeferenced maps, the authors also employed maps published on the website Arcanum Maps – The Historical Map Portal (Timár et al., 2006) which ensures good readability of the materials.

The coordinate system S-JTSK Krovak East North (EPSG: 5514), commonly available for current mapping in the Czech Republic, was used at this stage of the research. First, map keys from all of the mapping cycles were analyzed to allow designing the structure of the ferry database. The mapping itself was carried out using the on-screen method in the ESRI ArcGIS software (Dostál et al., 2021).

Besides the classic map marks in the river courses, toponyms – mostly with German names – were observed on the maps; the more recent mappings already exposed names in Czech. In each of the periods studied, individual objects were located, and their positions were assumed to be identical within the observed continuity of objects, at a distance tolerance of 50 m. Regarding inter-object distances greater than 50 m in each period, separate, independent ferry sites were identified.

Based on the above process, a database of river ferry grounds in the Czech Republic was prepared, containing all localities in the present-day Czech Republic where cross-river ferries were shown in the topographic maps (Dostál et al., 2021). When creating the database, we also used some auxiliary archival sources, possibly toponyms listed on old maps (Panecki, 2023).

3.3 Model areas

The cultural and historical values of the ferry sites were investigated within two model areas in the Czech Republic, namely, the rivers Morava and Dyje in Moravia and on the section of the Labe River that runs between the Bohemian towns of Mělník and Kolín (Fig. 1). These regions or subregions were traditionally markedly industrial and agricultural, involving intensive transportation of goods, materials, and people. Simultaneously, it has to be noted that the relevant geographical segments embody parts of the most significant watercourses in the historical lands of Bohemia and Moravia. On the Morava and Dyje rivers, 17 sites were examined,

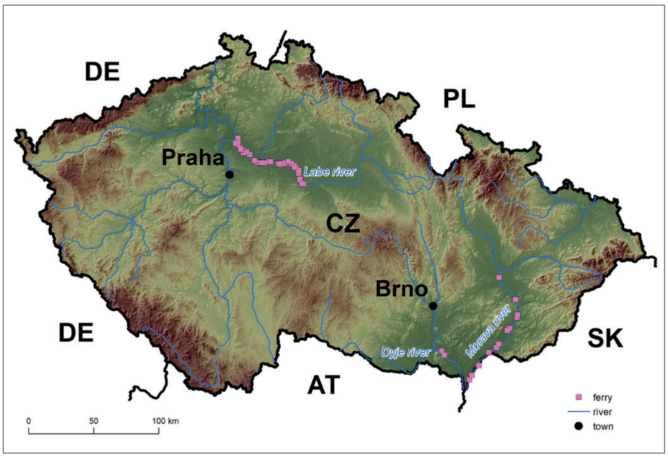

Fig. 1: The ferry locations along the Labe, Morava and Dyje rivers
Source: Authors' own elaboration

and the selected portion of the Labe river covered 48 sites. Such numbers then reflect a major density difference between the lands, with the actual choice of localities being an influence on some specific values following the applied methodology.

The three rivers under review are among the main watercourses draining the territory of the present-day Czech Republic. Since time immemorial, they have been arteries of life and trade, and therefore there have historically been interests in implementing their water management modifications, motivated by economic development, improving transport conditions and protecting the surrounding area from floods. These efforts can be traced back to the High Middle Ages on the Labe River, and to the mid-17th century on the Morava and Dyje. However, a systematic approach to the modifications of these rivers was not taken until 1896 on the Labe (and Vltava) River and until 1870 on the Morava and Dyje. The main focus of regulatory work, including full navigability, including the construction of navigation steps and the remodeling of the bed of the middle course of the Labe River under study, took place from 1911 to 1954, with the period between the world wars being key (Fošumpaur et al., 2020). The main regulatory works on the Morava river were primarily aimed at flood protection and were launched after 1905. Most of the river modifications were implemented by the beginning of World War I (1914), although in some sections the works were extended until 1941 (Brázdil et al., 2011). The important industrial company Baťa sought to make the Morava River navigable, which had a shipping channel built on part of the river between 1934 and 1938. It was primarily intended to facilitate the transport of lignite from the Ratíškovice coal field (downstream of the Strážnice area) to the Baťa factories in Otrokovice and Zlín (upstream). It was also to serve as a source of water for irrigation. Cargo transport ceased after only a few decades of operation as soon as early 1960s but nowadays the channel found further employment for water management purposes and as a tourist attraction (Machar, 2013; Havlíček & Svoboda, 2022).

4. Results

In the Moravian part of the research, we focused on a total of 17 ferry sites (Fig. 2), the average value of cultural-historical significance was 8.24 (out of a potential maximum of 27 points). Some ferries achieved very low overall cultural-historical values (total value 1 and 2). These were mainly ferries that had little historical significance for the transport of people or cargo, were not connected to any significant roads and currently no remains of them have been preserved. On the Morava and Dyje rivers, the Moravská Nová Ves – Kopčany ferry achieved the highest rating with a value of 17. This ferry had a long continuity of operation extending into the 18th century, originally connected two historical countries (Moravia and Hungary) across the Morava River, some landscaping is still visible in the terrain, a road is preserved on both sides of the river, as well as the ferryman's house, which is still inhabited today. The Nové Mlýny ferry site also achieved very high overall values, which received a higher rating also due to the historical significance of the tragic event in which elementary school children died in 1936. At the same time, it was a ferry of solid importance for the transport of materials and people, and it also achieved a longer continuity of operation. A high value was also recorded for the Lanžhot - Brodské ferry, which served for a long time as one of the possible connections between municipalities in two different countries (Moravia, Hungary). The gamekeeper's lodge, which originally also served the ferryman's needs, has been preserved here to this day. Five ferries achieved a total of 13 points in the overall assessment of cultural and historical significance. However, their point ratings are based on different cultural and historical values (Fig. 2).

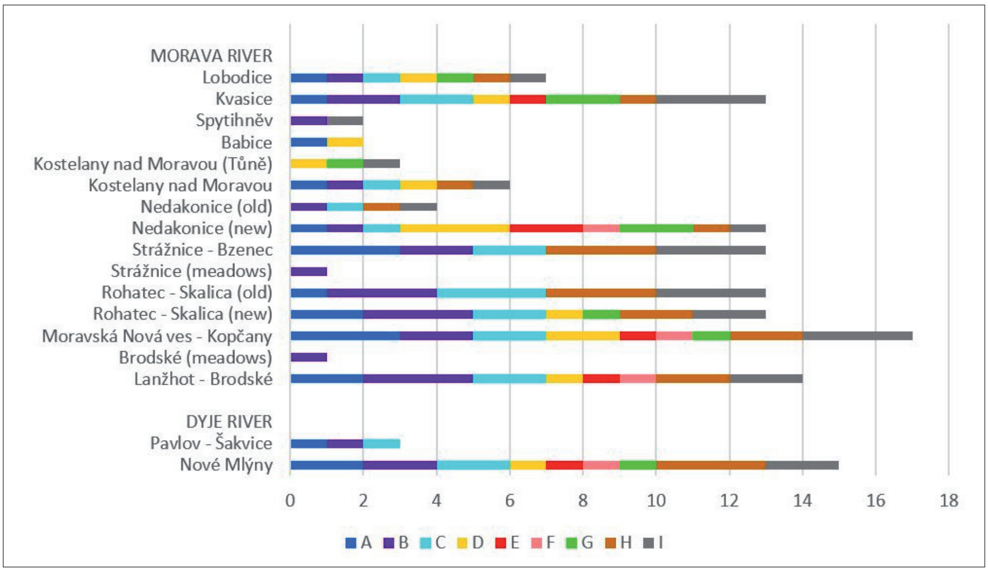

Fig. 2: The ferry grounds on the Morava and Dyje rivers, with both the cultural-historical values relating to the individual types and the overall cultural-historical value – sorted by river flow (Notes: A – typology value; B – technological flow value; C – system links value; D – authenticity value; E – architectural value; F – art historical value; G – landscape value; H – historical value; I – age value; total – complete art historical value of the area)
Source: Authors' elaboration

The Strážnice–Bzenec ferry was historically one of the most important and frequented ferries, connecting two important cities in the region, Strážnice and Bzenec, and was also typologically valuable, it was a large barge with a capacity of around 30 to 40 people, also for freight transport and using a guide rope. Historically and in terms of continuity, it was a crucial ferry in the region. Unfortunately, nothing has been preserved from this ferry at present. The Rohatec–Skalica old ferry has a similar characteristic. The Nedakonice new ferry was operated only in the 20th century, so it has lower continuity and also historical significance. However, it has a high value of authenticity and architectural value, the ferryman's house is still preserved here, as well as a typical geomorphological shape in the form of a bay (Fig. 3). In terms of the types of cultural-historical values of ferries, type B – technological flow value (average 1.47 out of 3) reaches the highest values on the Morava and Dyje rivers. The connection of some municipalities was very frequent, in addition to the transport of people for work, education or church activities, there was also a lot of transport of goods, earlier on horse-drawn carriages, later also by cars. Very high values were achieved for continuity values (average 1.41 out of 3), several ferries were operated for two or more centuries, and for several ferries the tradition of ferry operation is documented since the Middle Ages. High values were also achieved for C – system links value (average 1.18 out of 3), long-distance trade routes were connected by the Rohatec–Skalica ferries, in certain cases access to the railway was also crucial (e.g. Strážnice–Bzenec ferry). The same average was recorded for H – historical value (average 1.18 out of 3), while historical importance was high both for traditional important ferries at larger settlements (Strážnice–Bzenec ferry, both Rohatec–Skalica ferries), and for locations with a significant historical event (Nové Mlýny). Typologically, large ferries with a high capacity for transporting both people and cargo were particularly appreciated (Fig. 2). D – authenticity value for ferries on the Morava and Dyje rivers reached lower average values, and preserved objects in the form of ferryman's objects or geomorphological shapes are rather rare. An architectural value can be presently sought only in the gamekeeper's lodge at the Morava River-based Lanžhot–Brodské ferry grounds: the lodge has been a historical segment, and its past roles also included that of a traveller's inn. Some of the current building's components and details, such as the window shutters and portions of the plaster, have an art-historical value, a property that is even more comprehensively embedded in the memorial to the victims of a 1930s ferry accident at Nové Mlýny. Landscape values have been assigned to 7 sites, especially as regards the view layout, visual quality, or geomorphological shape.

From the perspective of character and exceptionality, the most notable of the ferry sites is that in Nové Mlýny, which incorporates a memorial to the victims of a 1936 tragic attempt to cross the flooding river (Figs. 4 and 5); the event claimed the lives of 32 people, including 31 school-age children. The memorial was commissioned by the first Czechoslovak president, Tomáš Garrigue Masaryk.

Fig. 3: The Nedakonice new ferry grounds with the preserved anthropogenic formations, including the water slip road and ferryman's house. Photo: I. Dostál

The Bohemian part of the research project includes the middle section of the Labe River, between the cities of Mělník and Kolín. A total of 48 ferry sites were assessed (Fig. 6), the average value of cultural-historical significance was 8.38 (out of 27), i.e. slightly higher than on the Morava and Dyje rivers. The facilities were established in a density significantly higher than in the Moravian regions. The Bohemian regions currently offer slightly more unique structures with a high typological value (A – typology value average 1.25 out of 3) than on the Morava and Dyje rivers. In the past, ferry transport embodied a relatively common possibility of crossing the river in this geographical sector; in the given context of typological value, we focused mainly on freight ferry areas with additional technical facilities. The highest average values in the

Fig. 4: The Nové Mlýny ferry site memorial
Photo: I. Dostál

Fig. 5: An information signboard presenting a poem and describing the accident of 1936 at Nové Mlýny ferry site
Photo: I. Dostál

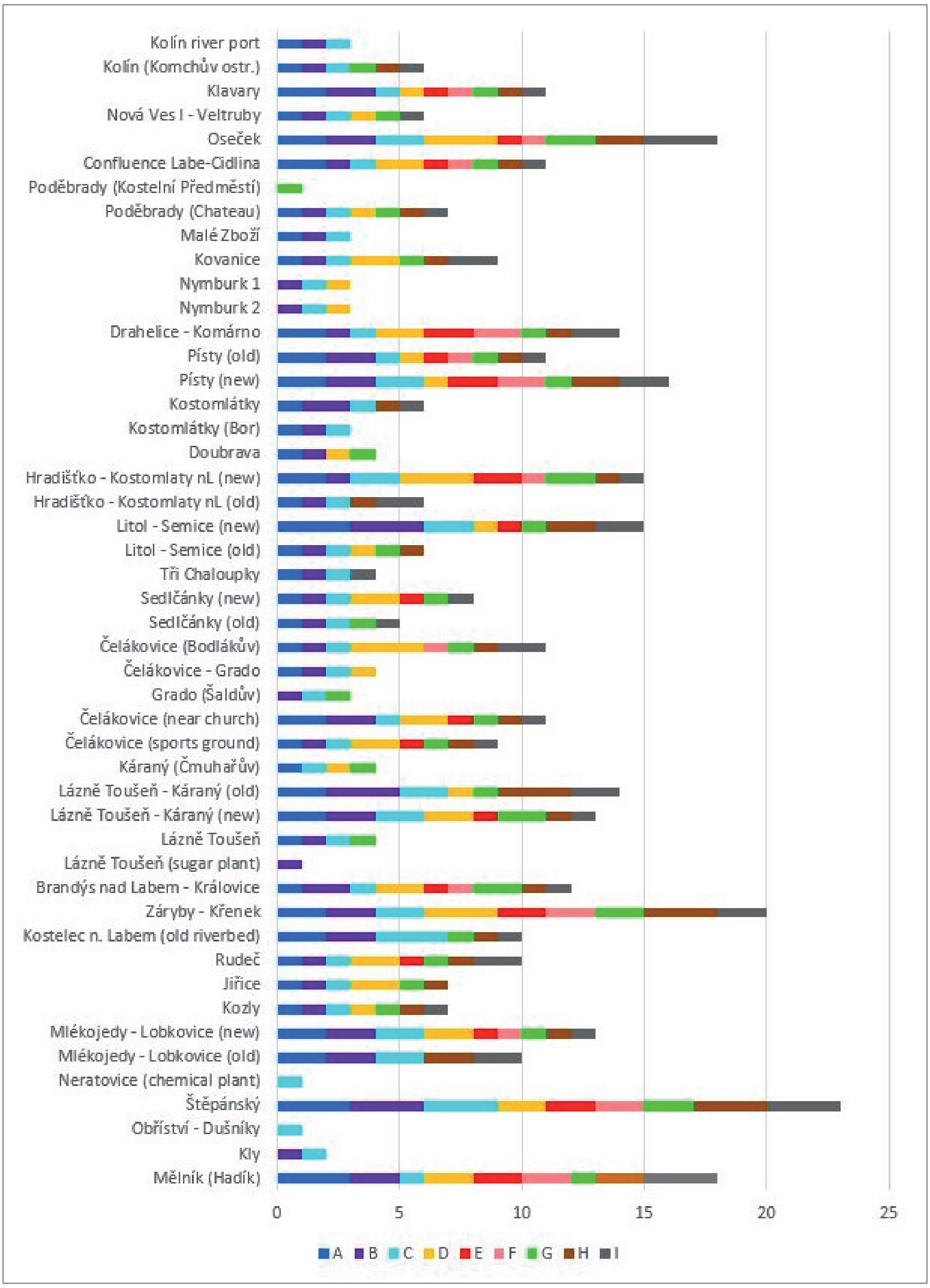

Fig. 6: The Labe River ferry sites, with both the cultural-historical values relating to the individual types and the overall cultural-historical value (Notes: A – typology value; B – technological flow value; C – system links value; D – authenticity value; E – architectural value; F – art historical value; G – landscape value; H – historical value; I – age value /continuity; total – complete art historical value of the area)
Source: Authors' elaboration

Labe River section are achieved by B – technological flow value (average 1.31 out of 3) ferries. It has been documented that ferries played an important role in the transport of people, materials and goods in some locations on the Labe River. Specific ferries were also linked to the development of industry and commuting to work. The most common purpose of the ferries was to connect the main regional roads and settlements and provide general accessibility.

Starting from the mid-19th century, the connection to the rail stations gradually came to the fore. C – system links value reached an average of 1.21 out of 3 on the Labe River, i.e. a slightly higher value than on the Morava and Dyje rivers. In the case of D – authenticity value, we can observe specific patterns in these areas, such as preserved ferry houses, which are currently used for permanent housing or cottages and replicas of original houses. Numerous anthropogenic river inlets are embedded in the banks along the studied section of the Labe River. Previously, these formations allowed for safe boarding and disembarking of the ferry outside the main current. The bays then increase the authenticity of the Labe River ferries and allow them to significantly outweigh other cultural and historical value classes (Fig. 6). In these locations with preserved objects, E – architectural value; F – art historical value are therefore also more significantly assessed. In general, the values of the criteria G, E and F are higher in the Labe River section than in the Morava and Dyje rivers.

Regarding the cultural-historical assessment, the most prominent values were revealed at Štěpánský ferry near Obříství village (Fig. 7); the ferry site provided for a traditional cross-river service to connect the Labe river's left bank with the imperial road, and one of its buildings has housed a traveller's inn that is still active today. The grounds, together with a major berth close by, were of substantial interest to boats heading for Germany. In the above-presented context, a peak cultural and historical value is found also in the Záryby–Křenek site, the main reason being that the ferryman's home has been reconstructed sensitively, including the original furnishings (Fig. 8). Both of the locations exhibit considerable importance in terms of their tourism-related and educational roles, especially where the focus is on the structural arrangement of old ferry sites.

Some culturally and historically interesting buildings are no longer exploited in original way, as they have been owned privately and ceased to fulfil their former functions. Such is the case with most surviving ferryman's homes, a large number of them having been converted into larger regular or part-time residences. To illustrate the process, we can expose a house of this type that has become a cottage, see Figure 9. The remains of some geomorphological formations, river bays in particular, are now usable exclusively in relation to minor informative projects; these may involve, for instance, designing data boards that tell the story of the ferry grounds by such means as exhibiting excerpts from archival documents, including topographic maps. An open potential is available in, above all, spots situated directly on hiking trails, as has shown on the disused ferry grounds at Lázně Toušeň (Fig. 10).

The average values for the individual categories of cultural and historical values range from 0.24 to 1.47 for the Morava and Dyje rivers (Tab. 1), and from 0.38 to 1.31 for the Labe River (Tab. 2; potential maximum was 3.00). The lowest average values achieved are E – architectural value and F – art historical value. These categories also have the highest zero value share as these are conditioned by the preservation of the buildings. On the contrary, the highest average values are achieved in both study areas in the case of B – technological flow value (Tabs. 1 and 2). The Morava and Dyje rivers have a significantly higher average for I – age value caused by the higher continuity of ferry operations in the past. In general, the average values for both study areas are also higher for categories A – typology value and C – system links value. The average and standard deviations are also high for categories H and I, where both the historical and age values are well distributed on a scale of all values from 0 to 3. In the case of ferries on the Morava and Dyje rivers, the standard deviation values are generally higher for categories A – typology value; B – technological flow value; C – system links value. In the case of ferries on the Labe River, the standard deviation is higher for D – authenticity value, which is indicative of the preservation of some ferry landforms and objects, but also of the existence of sites which vanished without traces.

The boxplot from the PCA analysis shows that the medians of the total cultural-historical values of individual ferries do not differ for the Labe, Morava and Dyje rivers (Fig. 11). More significant differences are recorded in the standard deviations, where their

Fig. 7: The restaurant Na Štěpáně near the village of Obříství: a part of the Štěpánský ferry facilities, possessing strong historical transport features and links (an accessory component to the imperial road and the river boat traffic). Photo: I. Dostál

Fig. 8: The ferryman's house at Záryby – Křenek: post-reconstruction, partially furnished. Photo: I. Dostál

Fig. 9: A preserved ferryman's house on the Labe River in Brandýs nad Labem, now used as a recreational facility Photo: I. Dostál

Fig. 10: Typical anthropogenic shape at the former ferry on the Labe River near the village of Lázně Toušeň. Photo: I. Dostál

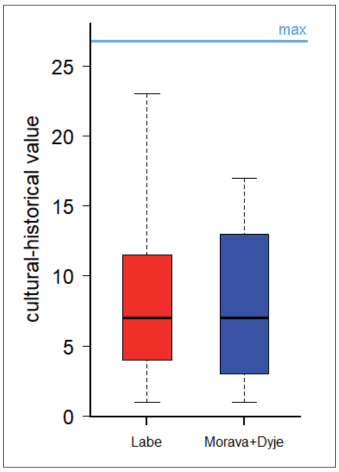

Fig. 11: The boxplot from PCA for total cultural-historical values of ferries in Labe River, Morava and Dyje rivers
Source: Authors' calculations

variability is higher for the Morava and Dyje rivers (colored bars in the graph). The dashed line records the maximum and minimum for the total cultural-historical values of ferries. The minimum in both areas reached the value 1. The maximum value for the Morava and Dyje rivers was 17, for the Labe River the maximum was 23 (out of a potential maximum of 27). Principal Component Analysis replicates the overall cultural-historical value on the first axis and shows a large variability of ferries on the Morava and Dyje rivers, especially along the second axis (Fig. 12). The composition and variability of cultural-historical values do not differ between ferries on different rivers (tested in multidimensional space; PERMANOVA, PERMDISP).

Only some variables are correlated within the cultural-historical values (Fig. 13). The most important are architectural vs. art-historical value and then historical value vs. continuity. In the first case, the connection between architectural value and art-historical value is given by the preservation of any objects related to the operation of ferries (ferryman's house, inn, boat or raft, stairs or access to the water and other elements). In the case of

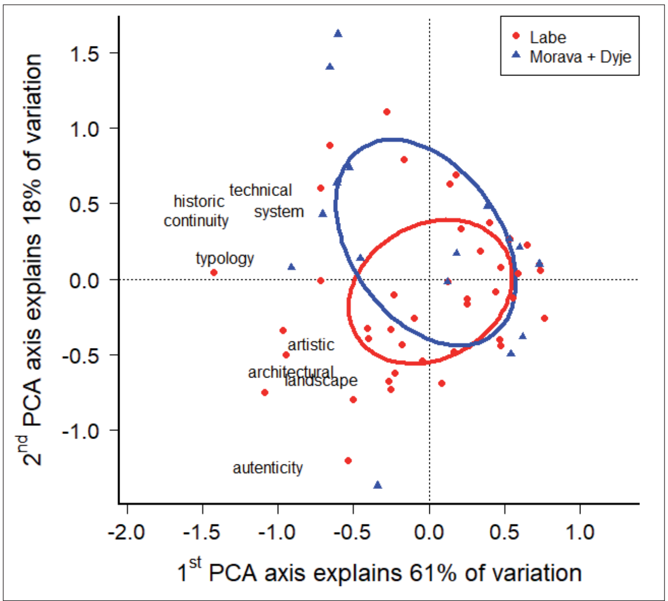

Fig. 12: Principal Component Analysis (PCA) for total cultural-historical values of ferries in Labe River, Morava River and Dyje River
Source: Authors' calculations

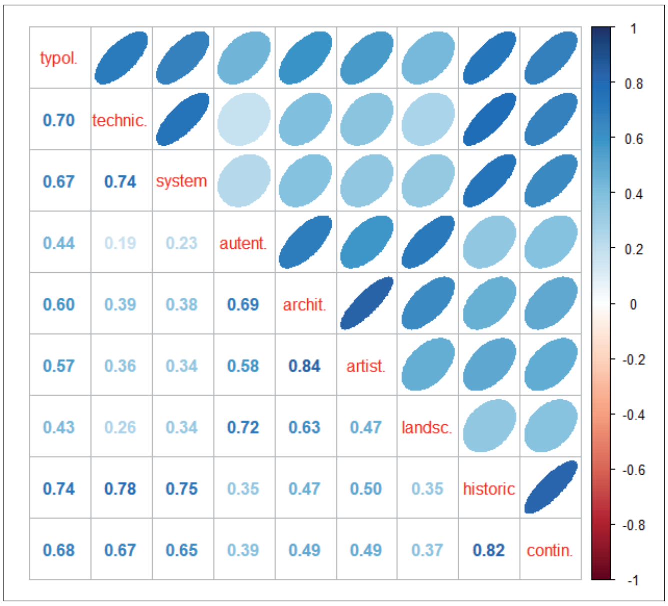

Fig. 13: Correlation of individual cultural-historical values of ferries
Source: Authors' calculations

Cultural-historical value	A	B	C	D	E	F	G	H	I
Average (out of 3)	1.12	1.47	1.18	0.76	0.35	0.24	0.53	1.18	1.41
Frequency value 0	5	2	5	7	12	13	10	6	4
Proportion value 0 (%)	29.41	11.76	29.41	41.18	70.59	76.47	58.82	35.29	23.53
Mean deviation	0.75	0.79	0.80	0.63	0.50	0.36	0.62	0.93	0.96
Standard deviation	0.96	0.92	0.92	0.81	0.59	0.42	0.70	1.10	1.09

Tab. 1: Statistics of individual categories of values – Morava and Dyje rivers (n = 17; Notes: A – typology value; B – technological flow value; C – system links value; D – authenticity value; E – architectural value; F – art historical value; G – landscape value; H – historical value; I – age value /continuity; total – complete art historical value of the area)
Source: Authors' research and calculations

Cultural-historical value	A	B	C	D	E	F	G	H	I
Average (out of 3)	1.25	1.31	1.21	1.08	0.50	0.38	0.83	0.83	0.98
Frequency value 0	8	4	3	17	30	35	14	19	17
Proportion value 0 (%)	16.67	8.33	6.25	35.42	62.50	72.92	29.17	39.58	35.42
Mean deviation	0.66	0.58	0.45	0.82	0.63	0.55	0.49	0.66	0.69
Standard deviation	0.76	0.67	0.82	0.90	0.69	0.68	0.75	0.88	0.90

Tab. 2: Statistics of individual categories of values – Labe River (n = 48; Notes: A – typology value; B – technological flow value; C – system links value; D – authenticity value; E – architectural value; F – art historical value; G – landscape value; H – historical value; I – age value / continuity; total – complete art historical value of the area)
Source: Authors' research and calculations

longer continuity of ferry operation, it is also possible to evaluate the greater historical significance of the object, so this correlation is also logically justifiable.

5. Discussion

The registered ferry sites with the accompanying database of old topographic maps embody a suitable basis for assessing the significance of the relevant cultural heritage. The precise localization of the buildings and facilities allows performing follow-up archival and field research projects to assess objectively the potential of the river ferry sites for cultural heritage. From the perspective of cultural heritage, analyzing transportation entails involving entire sections of historic roads with the relevant complementary structures. The roads are seen as a heritage, cultural, and identity reference, which generally captures diverse historical processes (Molina-Castańo et al., 2023). In particular, historic bridges are among the most frequently protected cultural sites (Gagliardi et al., 2022; Manos et al., 2019). When discussing and enforcing their protection, experts focus on maintaining, conserving, and safely reconstructing the segments that feature cultural-technical prominence (Gagliardi et al., 2022).

The results of the research showed that the assessment of the cultural and historical significance of river ferries is methodologically more complicated than the assessment of industrial buildings or water management structures (Ryšková et al., 2022; Matěj & Ryšková, 2018). The main complication is the lack of preserved objects directly related to the operation of river ferries, very rarely the ferryman's house is preserved, sometimes a nearby inn or a building with technical facilities. This then has a direct impact on the very low values of E – architectural value and F – art historical value. The lack of physical remains is most evident at ferry sites identified in the earliest historical periods that have not survived to the present day. This is due to the fundamental transformations of the landscape along the watercourses that were the result of economic regulations and flooding (Brázdil et al., 2011; Fošumpaur et al., 2020). Conversely, in sites where ferries operated in the period after the flow regulation, physical remains are common. The greatest correlation was also demonstrated between values of E – architectural value and F – art historical value, but it is still appropriate to preserve both of these values in the methodological procedure, because the localities of ferries with these high values are very valuable in the protection of cultural heritage.

The fundamental finding from this research can be considered that ferries from older periods have a solid age value, but do not have preserved authenticity, because the area has often undergone significant changes and regulation of watercourses. The initial limit may therefore be the suitability of the selection of the area, in the case of this study, it was rivers that are mainly tied to lowland valleys and wide floodplains, which lack geomorphological diversity in the context of river regulation. On the contrary, interesting anthropogenic shapes remain after ferries, which add diversity to the landscape, the uniformity of the banks of regulated rivers was thus disrupted in the 20th century by the bays of ferries. Preserved anthropogenic shapes can be used for education and use in tourism (Dostál & Havlíček, 2021).

Some ferry sites exhibit a dynamically utilizable potential for preserving specific facilities in the landscape, such as bays with water access paths made of historically valuable paving stones. Similarly, in this case, it is also possible to associate the research with an investigation of the building stones (their origins and use) or with examining the geomorphological shapes (Kubalíková & Zapletalová, 2021). In recent years, in the landscape geotourist and geoeducational activities are designed, the emphasis being on a comprehensive promotion of natural and cultural heritage. Geotourism has been conceptually developed also in urban areas (Kubalíková et al., 2020). Some defunct ferry sites can thus be considered spots of geotourist significance. Importantly in this context, the safeguarding of intangible cultural heritage is as important as the protection of tangible cultural heritage (Demir, 2021). While bridges over the river have a much higher level of preservation, including historical and architectural values, ferries have a significantly lower level of preservation. Historical events associated with ferry sites such as Nové Mlýny 1936 are rare. By definition, ferry sites, whether defunct or preserved, do not possess the fundamental cultural-historical significance of road components, such as China's corridor bridges (Knapp et al., 2020) or study of the historical and structural aspects of the Imperial Bosnian Road with significant stone bridge (Akšamija et al., 2024), some of the ferry sites may nevertheless become classified and interpreted as valuable structures worth promotion.

Therefore, new technologies may come to the play to promote relics and remains of the past. Presentations of virtual cultural heritage artefacts are often communicated via interactive digital storytelling. The synergy of a storied narrative embedded within a 3D virtual reconstruction context has a high consumer appeal and edutainment value, and this finding is conveniently implemented in, for example, a case study that describes the bridge diving tradition at Stari Most, the historic bridge in Mostar, Bosnia (Selmanović et al., 2020). Similarly, modern computerized procedures could allow exposing effectively the outcomes of the research on ferries in the Czech Republic, with the old maps, plans, images, and facility details being the central primary sources. The tourism attractiveness of selected ferry sites is also enhanced via the classic ways, namely, by using information signs to advertise particular preserved elements (a ferryman's house, an inn, a bay, a water entrance, a ferry vessel, parts of the boarding pier, and other items). In our project, such facilities were documented at several locations within the model regions. The overall cultural-historical significance of the ferry site and its accessibility via tourist routes then determines its role in tourism: Locations that are better accessible and well-documented also offer more options for being included in the network of educational trails to broaden their instructive potential (Nevřelová & Ružičková, 2019).

6. Conclusions

The registration of historic ferry sites, accompanied with a database compiled from old topographic maps, possesses a relatively broad perspective in estimating the importance of the locations' cultural heritage. The actual mapping, the continuity of the facilities, and the historical context recorded on the maps deliver baseline yet worthwhile data concerning the cultural and historical value of specific ferry grounds.

Follow-up archival and field research at the sites, however, embodies an essential precondition for an objective assessment of the potential of the river ferry sites for cultural heritage. In field research, aspects of architectural value, landscape value, technological and art historical value are important to capture. From a tourism point of view, several interesting sites were found in the Labe River basin as well as in the Morava and Dyje River basins, where information signs with the history of the sites and maps or photographs were available. In the Dyje and Morava River basins these were the sites of Nové Mlýny, Rohatec, Lanžhot, in the Labe River basin these were the sites of Oseček, Záryby, Čelákovice and others.

In general, however, some knowledge and information about historical river ferries can be used to make the sites even more attractive for tourism. Nowadays, there are possibilities to promote the topic of historical ferries through digital map applications, or by locating objects on traditional digital tourist maps, by including sites in educational trails, and nowadays 3D technologies can also be applied.

Compared to methodologies for assessing the cultural and historical significance of industrial sites and water management facilities, the applied methodology for assessing river ferries has certain limitations and limits. Nevertheless, it is possible to apply this methodology in other locations, because the research results are applicable in practice.

The follow-up research is expected to offer viable options for comparing the cultural impact of the Bohemian and Moravian ferry grounds with that of relevant sites in other European countries or subregions. Such areas are characterized by a cultural and historical context resembling the Czech Republic's milieu, especially at locations where ferries were a truly indispensable means to cross the river. The applied methodology features a major potential for use in transportation research; cultural-heritage, history, and geography projects; tourism; and related provinces. Importantly, the approach is further refinable by substituting the binary criterion with a more precise range and via setting the weights of the individual factors.

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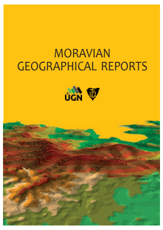

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Towards greener cities: Evaluating urban green space accessibility using the 3-30-300 rule exampled on the city of Olomouc (Czech Republic)

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Abstract

The 3-30-300 rule outlines key principles for urban greenery, emphasising its role in promoting human health, well-being, and quality of life. It calls for equitable access to green spaces and an integrated approach to urban development. This study introduces a transferable methodology for applying the 3-30-300 rule, focusing on Czech cities. A notable feature of the study is its usage of a deep learning tool combined with freely available public data. The methodology was applied to all residential buildings in the city of Olomouc, providing specific results at both citywide and individual rule-component levels. The study also addresses the rule's limitations, offering a realistic view of its practical application. This contributes to the broader discussion on the role of urban green spaces in creating more sustainable and liveable cities. The findings reveal that rule 3 is met for nearly all residential buildings in Olomouc. However, rule 30 appears unattainable in the city, with maximum neighbourhood canopy cover reaching only 22%. Only approximately 25% of residential buildings are situated within the recommended 300-metre radius of a park. Our research shows that the 3-30-300 rule is a feasible framework for measuring the availability of greenery in (Czech) cities; however, further methodological development is needed.

Keywords: 3-30-300, urban planning, green infrastructure, urban forestry, well-being

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1. Introduction

What should a contemporary city look like to provide everything a person of today needs? One can begin to answer this question by analysing the current form of our cities and objectively evaluating public space as a place that directly and indirectly influences every inhabitant and visitor. In cities the quality of the place where people spend their time is all the more important given that we are talking about an increasing number of people moving to cities (UNPD, 2019). Since the beginning of the 21st century there has been an ongoing trend of people moving to urban and highly urbanised areas, which has generally resulted in a steep increase in urbanisation and increased pressure and demands on the appearance, quality, and comprehensive planning of the urban environment (Samson, 2017). As early as 2018, approximately 55% of the world's population lived in urban areas (UNPD, 2019). The same upward trend continues and is not expected to change significantly in the near future (Samson, 2017). The growing number of people living in cities brings with it ever-increasing demands on the quality of the urban environment and the overall need to plan and adapt cities to make them the best possible places for people to live (Raihan, 2023).

Humans in urban environments are exposed to a large spectrum of stressors, ranging from insufficient light, air pollution, heat stress, the generally faster pace of a city, and the aforementioned large number of people. It is widely recognised that the availability of nature in the city, especially in the form of trees and green spaces, is becoming increasingly important for human health and quality of life (Astell-Burt & Feng, 2020; Astell-Burt et al., 2022). Urban green spaces can effectively influence the environment and reduce urban stress in a wide range of positive ways (UNECE, 2023; Browning et al., 2024; Nieuwenhuijsen, 2021). Green spaces in various forms – based on their functions, e.g. parks, sports fields, gardens, and private open spaces (Grabowski et al., 2022) – bring a range of benefits such as reducing temperature, improving air quality, reducing stress levels, promoting physical activity and social contact, and enhancing the physical and mental health of residents (Browning et al., 2024; Konijnendijk, 2021; Lottrup et al., 2015; Rugel et al., 2019).

In this respect, efficient distribution of urban green space across cities is currently one of the most important ways to improve the quality of the environment for urban dwellers and to improve the well-being of people exposed to urban stressors in general (Zhang et al., 2023; Grabowski et al., 2022). Despite similar measured temperatures, people consistently perceive forested areas as cooler than the surrounding environments. Forests can be used by urban planners as a nature-based solution to prevent our environment from causing heat stress (Gillerot et al., 2024). These benefits are invaluable for maintaining the viability of cities and the quality

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of life of their residents. Thus, access to green spaces has become an important added value for cities and almost a necessary and mandatory component of the urban environment (Weerasuriya et al., 2019). Today, every urban dweller can consider equal access to urban green spaces as a human right (Miles, 2022). Nevertheless, there are large differences in the availability of urban green spaces across cities and neighbourhoods, with different urban structures and diverse functions being very frequent (Konijnendijk, 2024; Kabisch et al., 2016). Such physical differences can, as in some US cities, even result in the inequality of accessibility to green recreational spaces for people of different social and ethnic backgrounds (Wen et al., 2013). Due to the aforementioned inequalities, there have been demands from the scientific community, urban planners, and municipalities, for a universally applicable and standardised approach to evaluating the availability of urban greenery, based on its lack and on people's needs (Konijnendijk, 2021). One modern approach to efficiently distributing green space in cities is to use the 3-30-300 rule, introduced in 2021 by Cecil Konijnendijk.

In this study, we will focus on the analysis of the 3-30-300 rule in terms of its real use and potential application for the Czech environment. The main objectives of this article are:

i. To create a general and transferable methodology that can be further applied in other (not only) Czech cities;
ii. To evaluate the fulfilment and significance of the 3-30-300 rule criteria in a medium-sized Central European city; and
iii. To discuss spatial differences between city districts with different urban morphology.

In this manuscript, we present a general methodology that is broadly applicable to different types of projects and research, specifically focused on planning the design of urban public spaces, taking into account the well-being of inhabitants and other factors affecting the value of individual places in a city. This methodology includes goal definition, data collection and analysis, strategic planning, implementation, and subsequent evaluation. We then apply this methodology to the specific case of the city of Olomouc, conducting a detailed analysis to demonstrate how these methodological approaches can be effectively used locally. This includes an evaluation of the results, which allows us to better understand the strengths and weaknesses of the applied methodology, and helps to clarify the limits of the application of the 3-30-300 rule in the Czech environment. Through this approach, we aim to provide a comprehensive overview of how theoretical approaches can yield practical benefits in the real world. This practical approach is grounded in the theoretical framework of the 3-30-300 rule, which offers measurable standards for enhancing urban green spaces and improving residents' quality of life.

2. Theoretical background

Before the establishment of the 3-30-300 rule, several principles and practices shaped the understanding of urban green spaces and their benefits. Urban greenery has historically been linked to climate moderation and public health; previous studies highlighted the importance of tree cover in mitigating urban heat islands (UHIs) and promoting biodiversity. For instance, research indicated that increased green coverage in urban areas is positively correlated with lowered temperatures and improved air quality (Kong et al., 2010). Furthermore, expectations for green space access had evolved, leading to informal community efforts and early policies aiming to ensure adequate greenery facilitated recreational opportunities and environmental justice (Koeser et al., 2024).

The background of the 3-30-300 rule arises from importance of greenery for urban health and well-being. Research shows that access to green spaces is associated with increased physical activity and improved mental health, contributing to overall community wellness (Konijnendijk, 2021; Nieuwenhuijsen et al., 2022). The proximity of parks encourages routine visits, which foster social interactions and physical activities, thus combating urban loneliness and related psychological issues (Konijnendijk, 2023). Furthermore, the presence of trees has been linked to environmental benefits, such as cooling of the urban environment (Janků et al., 2024), improved air quality (Selmi et al., 2016), and biodiversity support (Prevedello et al., 2017), making urban areas more resilient to climate change (Browning et al., 2024; Croeser et al., 2024). Moreover, green elements are perceived as comfortable and cooling features that contribute to overall outdoor thermal comfort (Lehnert et al., 2023; Květoňová et al., 2024). Additionally, the spatial distribution of urban green spaces significantly impacts their ecological effectiveness and the health of urban ecosystems. Research shows that a well-planned network of green spaces can improve ecological connectivity and resilience, enhancing urban sustainability, while optimising ecological service provision and the quality of urban living environments (Li et al., 2015; Chen et al., 2021). Conversely, fragmented green spaces can reduce urban ecological functions (Li et al., 2015), leading to issues like increased urban heat islands or urban heat load (Wang & Yang, 2024; Květoňová et al., 2024) and decreased biodiversity (Sharmin et al., 2024). Based on these findings, Konijnendijk addresses the need to integrate both natural and urban environments, which will increasingly become a necessary condition for well-developed cities that provide their inhabitants with the optimal living conditions (Konijnendijk, 2023; Konijnendijk, 2024).

An important aspect of the 3-30-300 rule pertains to its straightforwardness, providing a pass/fail benchmark for planners and communities to gauge urban greenness (Croeser et al., 2024). Ensuring that neighbourhoods meet these criteria can guide future urban planning initiatives, helping cities prioritise investments in green infrastructure (Torkfar & Russo, 2023). Additionally, such measures may promote equity in urban environments, as they ensure that even the most disadvantaged areas have essential access to nature, thereby bridging gaps in health outcomes across diverse socioeconomic groups (Koeser et al., 2024). The ongoing evaluation of urban access to nature through the 3-30-300 framework indicates that many cities worldwide fall short of these basic standards, exposing significant canopy deficits that necessitate urgent attention and action (Croeser et al., 2024). As urbanisation continues to accelerate, the relevance of the 3-30-300 rule as a tool for achieving greener, healthier cities is more important than ever.

The basis of the 3-30-300 rule is to emphasise three key aspects of urban green space in relation to human perceptions. Konijnendijk (2021) lists these three aspects as: the visuality of green space (i.e. people see and perceive the presence of green space), the proximity of green space (especially the degree of greening of the immediate neighbourhood), and the accessibility of green space (especially quality green space for leisure activities).

More specifically the first component, the ‘3’ in the rule, stipulates that from homes, schools, and workplaces, there should be a view of at least three trees. Several case studies have examined tree visibility and coverage in urban settings. The Master Plan for Barcelona's Trees (Guitard et al., 2017) was an early strategic document that aimed to increase urban tree coverage. In Florida, Koeser et al. (2024) focused specifically on tree visibility from windows. In Xiamen city, China, Zheng et al. (2024) analysed both tree visibility and compliance with canopy cover regulations. This criterion is designed not only to ensure a visual connection with nature but also to offer the psychological and aesthetic benefits that can arise from daily exposure to greenery (Browning et al., 2024; Nieuwenhuijsen et al., 2022). Empirical studies have demonstrated that such nature exposure is linked to reduced stress levels and improved mental health outcomes in urban populations, thereby endorsing the importance of the '3 trees' element as a public health as well as an environmental measure (Browning et al., 2024; Nieuwenhuijsen et al., 2022).

The second component, represented by '30', requires that at least 30% of a neighbourhood's area should be covered by tree canopy, an indicator that captures the density and quality of urban forests. This threshold is associated with multiple environmental benefits including improved local microclimates, reduced urban heat island effects, and enhanced air quality, which, in turn, indirectly support human health and social cohesion within communities (Croeser et al., 2024; Konijnendijk, 2023). It serves as a benchmark for urban planners to evaluate and compare neighbourhoods, ensuring that adequate tree cover is maintained or improved over time and thus acts as a driver for sustainable urban development (Browning et al., 2024; Konijnendijk, 2023).

The final component, denoted by '300', mandates that all residences be located within a 300-metre walking distance to the nearest public park or green space. This parameter is grounded in the notion that proximity to accessible green space increases opportunities for physical activity, social interaction, and leisure, which are all critical determinants of public health (Koeser et al., 2024; Croeser et al., 2024). A 300-metre distance is essentially equivalent to a five-minute walk, making it a practical and easily communicable standard to ensure that residents can regularly enjoy the benefits of urban greenery (Koeser et al., 2024).

Overall, the 3-30-300 rule is an emerging and promising framework designed to guide urban planners in the advancing application of green infrastructure in all types of cities, thereby enhancing the accessibility and benefits of urban green spaces. The main objectives and outcomes of applying the principles of the 3-30-300 rule should be to ensure equitable access to green space, promote sustainable development, and improve the environmental quality of individual urban areas and cities as a whole.

3. Methods and data

In 2021, Cecil Konijnendijk presented the rule of 3-30-300 for the first time (Konijnendijk, 2021). In 2023, he presented Evidence-based guidelines (Konijnendijk, 2023), and in 2024, Browning et al. (2024) presented an article about measuring the 3-30-300 rule. The recommendations from Konijnendijk's guidelines are listed in the methodology sections of each of the components, and we are applying them to the methodology we are proposing. Based on the guidelines we considered the most appropriate data sources, the advantages and disadvantages of each source are listed in Table 1. The key data source for analysis is public data, making this rule affordable for local policymakers. We use ArcGIS Pro and its tools to analyse the data.

3.1 Application (study area)

After establishing all the criteria (see 3.2, 3.3, 3.4), the rule was applied to the city of Olomouc. Individual criteria for specific parts of the rule were tested within sample areas (Fig. 5). Olomouc, situated in the eastern part of the Czech Republic, has a population of 102 thousand inhabitants and is the sixth largest city in the country (ČSÚ, 2024). Covering a total area of 103 square kilometres, the cadaster of Olomouc features a mix of agricultural areas (55%), urbanised land (31%), forests (11%), and water bodies (2%). A map of local climate zones (Geletič & Lehnert, 2016) is attached for a better understanding of the area (Fig. 1).

The city's history dates back to the 10th century. The historic core strongly reflects the influences of city fortifications that separated this part from the rest of the city until the mid-19th century. The historical centre primarily fulfils administrative and commercial functions and contains two of Olomouc's largest squares. This area was declared a cultural heritage site in 1971 (Ptáček et al., 2007). The historical city centre is surrounded by older residential buildings and a ring of parks (Smetanovy Sady, Bezručovy Sady and Čechovy Sady), which reflect the city's natural response to the need for green spaces through history (Daniel & Jirmus, 2023). The inner structure of the city was developed in the late 19th and the first half of the 20th century in three sectors, when it was mainly tenement and residential houses and functional buildings that were built north and south of the city's core. Villa districts with terraced houses were built in the west and east of the centre at the turn of the 19th and 20th centuries. The highest percentage of the

	Methods	Sources	Advantages	Disadvantages
Rule 3	Land cover maps	Urban Atlas – street tree layer	Data source for European cities (conurbation with 50,000 inhabitants and more)	Data only for locations included in the Urban Atlas, polygon layer, only larger groups of trees included, impossible to detect single trees
	Remote sensing + deep learning	ČÚZK – orthophoto	This type of data suits the tree detection tool, can detect single trees, polygons and point layers, can calculate shape area, data for every municipality in the Czech Republic, low percentage of errors	Incorrect count of trees in a group of trees, some of them are detected incorrectly
	Tree inventories	Terrain mapping	Accurate results	Impossible to cover the whole city, time-consuming, impossible to map trees on private property
	Questionnaires	Survey	Real count of trees from a window	Very subjective, depending on a chosen window, impossible to create the analysis for the whole city
	Window-view analysis	Photographies	Real count of trees from a window	Very subjective, depending on the chosen window, impossible to create the analysis for the whole city
Rule 30	Land cover maps	Urban Atlas – street tree layer	Data source for European cities	Data only for locations included in the Urban Atlas, only larger groups of trees included, inaccurate results
	Remote sensing + deep learning	ČÚZK – orthophoto	This type of data suits the tree detection tool, can detect single trees, polygons and point layers can calculate shape area, data for every city in the Czech Republic, low percentage of errors	Incorrect count of trees in a group of trees, some of them are detected incorrectly
Rule 300	Land cover maps	Urban Atlas – urban green space	Data source for European cities	Data only for locations included in the Urban Atlas, areas of UGS are inaccurate
		Cadastral plans	Data available for every municipality in Czech Republic, concrete data	Plans are from different year, need to check the actual state

Tab. 1: Methods and sources suitable for every part of the rule 3-30-300
Source: Authors' conceptualisation

population (more than 40%) lives in housing estates, either built as planned in the socialist era between the 1950s and late 1980s (in the northern, western, and southern parts of the city), or as new commercial development projects built mainly in peripheral areas or in close proximity to housing estates. Industrial zones dot the city's outskirts (Fig. 1).

In this study we analysed only the area of compact development (see Fig. 2). A compact city is defined as an area with an urban character of development, separated from suburban and rural areas. This concept includes higher density of buildings and a mix of functions such as housing, work, shops, and services, allowing residents to cover most of their daily needs on foot, by bike, or using public transport. The compact city promotes the sustainability of urban spaces, reduces car traffic, lowers emissions, and revitalises brownfields (Halás et al., 2013). The compact city area of Olomouc is approximately equivalent to one third of the administrative area (Fig. 2).

3.2 Rule 3

Browning et al. (2024) evaluated a Window-view analysis as the best method for determining 3 trees rule criteria, but by using this method, it is only possible to cover some of the city and it is very subjective. Tree inventories were chosen as a fair method, but there are many types. One option is to use public tree

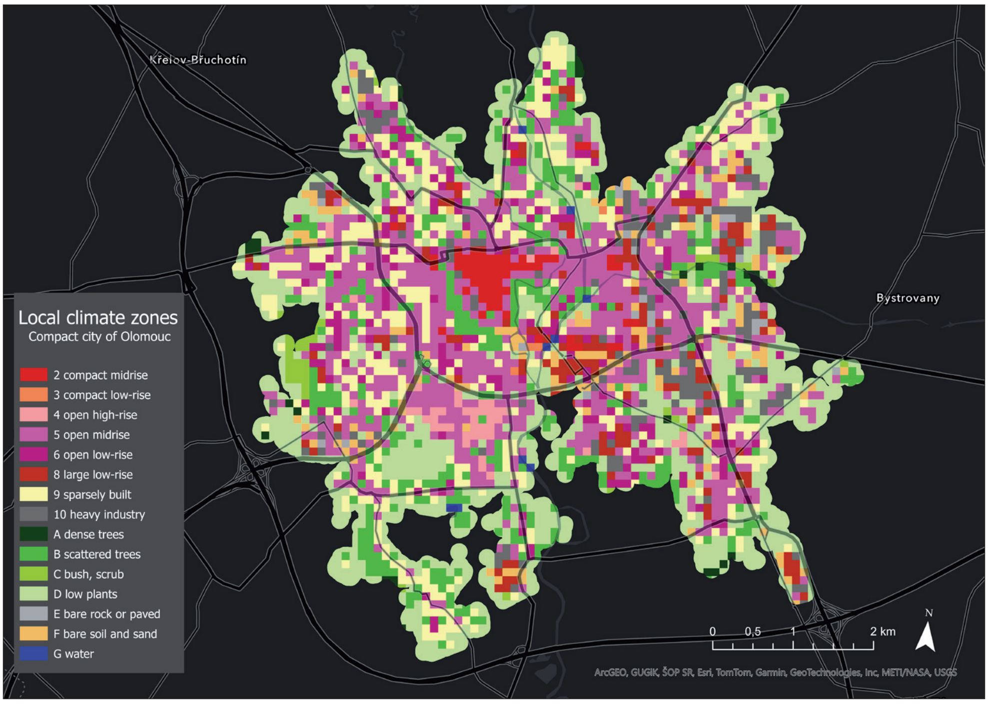

Fig. 1: Local climate zones in Olomouc (compact development used for the rule 3-30-300)
Source: Geletič & Lehnert (2016), authors' elaboration

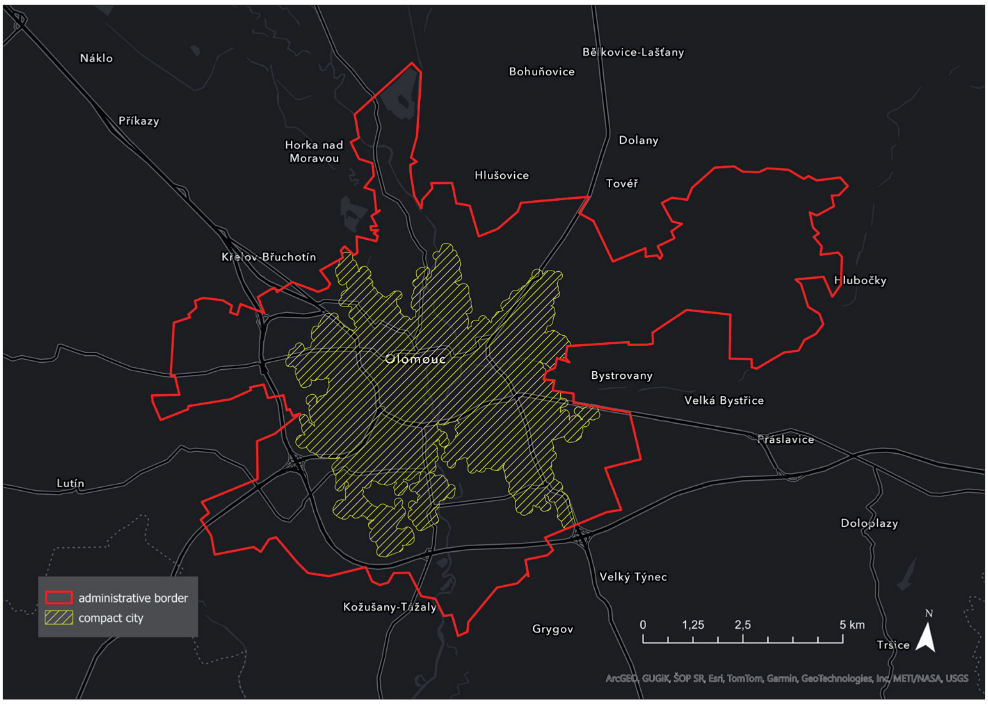

Fig. 2: Comparison between the administrative border and the compact city border (Olomouc)
Source: ArcČR 500 (2003), authors' elaboration

inventories, which are not available in all cities and mostly do not include non-public green infrastructure. Questionnaires are not ideal for reaching our goals because covering every address point in the city is not possible. Further, the Urban Atlas by Copernicus provides a polygon street tree layer; nevertheless, tree polygons do not reflect tree location correctly, and they show only groups of trees, so it is impossible to recognise single trees (Tab. 1). For this analysis, trees within 30 m of the building are counted. The choice of the 30 m distance is explained below.

Therefore, we decided to create inventories based on public data using deep learning tools. Esri provides the Tree Detection tool, which was focused on different types of forests and on data from the National Ecological Observatory Network (Weinstein et al., 2019; Weinstein et al., 2021). This deep learning tool is trained on 8-bit, 3-band high-resolution (10–25 cm) raster data. As an input for tree detection, we use orthophoto based on aerial imagery from the year 2023, which is free to download from the Czech Office for Surveying, Mapping and Cadastre (ČÚZK). The 'orthophoto' data resolution is 12.5 cm per pixel, which is well-suited as an input for the Tree Detection tool (ČÚZK, 2024a). The second data source for analysing the rule 3 is 'RÚIAN' (The Registry of Territorial Identification, Addresses and Real Estate). This source provides polygon layers of residential buildings so we can apply rule 3 to every residential building in the city.

In this methodology, there are a lot of variables that need to be tested. For this case we created six sample areas in Olomouc (Appendix 6). These areas are based on types of development in the Czech Republic (Ministry for Regional Development, 2022). The sample areas include: built-up areas of detached houses, the historical centre, housing blocks, street types, terraced houses and housing estates.

The Tree Detection tool is part of deep learning tools in ArcGIS Pro. As an output we have polygons with two attributes. The first attribute is a 'Shape area' and the second, more important, is 'Confidence'. For counting trees, we convert the polygon layer of detected trees to the point layer. The values of Confidence are from 0 to 100. The higher value of confidence means the higher confidence that the detected object is a tree.

First, we had to ensure that the objects detected were trees. The tree detection tool was utilised to identify false positive and false negative objects in the sample areas, with the assistance of orthophotos. Objects that were detected as trees but were not in fact trees are classified as false positives (e.g. chimneys, cars, pools, etc.), while objects that were trees but were not detected as trees are classified as false negatives. The specific proportions in each sample area are shown in Appendix 1–5. A correction of the detected object was needed, based on values of confidence. We started observing the object for the value 10–100 (Confidence), and then we continued with the next intervals. We were looking for incorrectly defined objects in 5 intervals of Confidence (Fig. 3). For the most accurate results, we chose to count objects with confidence greater or equal to 25. At this threshold, we observed the lowest percentage of error, with an almost equal proportion between false positive and false negative objects (Fig. 3). At the same time as the confidence value increases, well-established trees were selected and small trees were not included, which was verified by field research in all sample areas (Appendix 7).

Another task was to determine the ideal distance for counting trees. We tested the buffer zones for each residential object in sample areas at 10, 20, 30, 40, 50, and 60 metres distances. For each distance we calculated the overlaps with other buildings. Based on the analysis of overlaps we used a buffer of 30 metres distance from the buildings. The proportion of overlaps increases more rapidly in buffer zones bigger than 30 metres (Fig. 4). We also tested the suitable buffer distance visually. We created buffer zones for every residential building in sample areas and

Fig. 3: The graph of errors (total error and the proportion between false positive and false negative in the detected objects)
Source: Authors' research and calculations

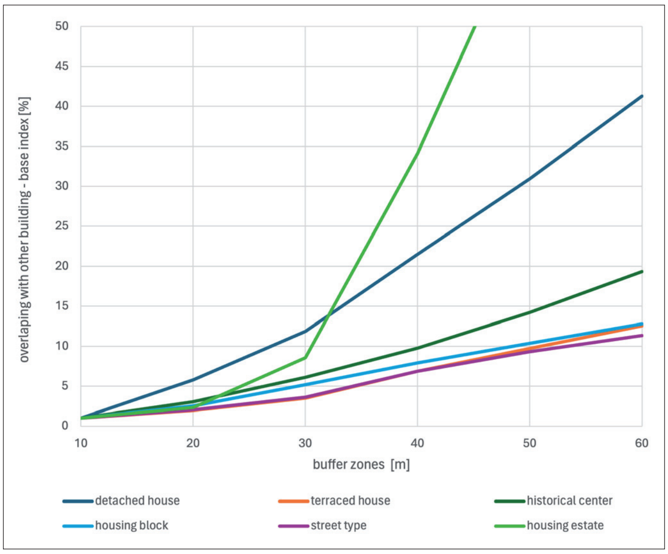

Fig. 4: Base index of calculating overlaps with another building for each sample area
Source: Authors' research and calculations

observed the most appropriate distance. The average distance between buildings is about 30 to 40 metres. This means we can see trees approximately 30–40 metres from the window. Based on these two methods we calculated the number of trees in 30-metre buffer zones.

Finally, we calculated the number of trees detected by tool tree detection after correction in a 30-metre buffer zone. For this calculation we used the tool 'Summarise Within'. We calculated the sum of trees for every single residential building in the selected city. Based on this analysis, we can say that there are at least three trees in a buffer zone for every single residential building. The biggest advantage of this method is that we can replicate it in every Czech municipality, and we have results for every residential building.

3.3 Rule 30

Another part of the rule involves calculating the percentage of canopy cover in a neighbourhood. To define neighbourhood, Chaskin (1997) and Weiss et al. (2007) recommend the use of geographically bound homogenous areas of limited size, or administrative units. Originally, we carried out tests using the smallest administrative units in the Czech Republic, but this has some disadvantages. These administrative units are of different sizes, and there is a problem with units that are on the borders of buildings and landscapes because it was possible that we could count trees outside the compact development, which would give us inaccurate results. Eventually, as a neighbourhood, we used a 300-metre buffer zone based on the WHO area for 5 minutes of walking. The 300-metre distance is also connected with the rule 300.

As a layer of canopy cover, we considered using data from the Urban Atlas because it has a polygon street tree layer. We compared it with other remote sensing data and field surveys, however it did not represent well the real distribution of trees, as only larger groups of trees were included in this layer. We decided to use the same layer as we used for rule 3 (see Section 3.2). The data obtained by the tree detection tool also contains the shape area attribute, providing the crown area (canopy) of each tree. Then we used the summarise within tool to calculate the sum of the shape area in each buffer of the dwelling. Based on this source we could calculate canopy cover in a 300-metre neighbourhood. Again, we could calculate canopy cover for every residential building in the selected municipality.

3.4 Rule 300

Network analysis was used for the application of the 300-metre rule. The source layer for analysis consists of data from the ZABAGED (Basic geographical database) package, specifically streets and roads. Access points were created for individual green spaces to enhance the quality of the analysis results. These access points were selected as the intersections between the road network and the urban green space (UGS) polygons. The definition of public urban green space plays a key role in the case of rule 300. Parks and other green spaces used for recreation need to be carefully selected and a basic knowledge of the area is important. Available orthophoto imagery is also used to verify the selection. Because the ZABAGED data does not provide the layers of UGS, the selection of green areas was based on cadastral plans provided by municipalities. This data source was chosen because cadastral plans are available for every municipality and allow efficient identification of green areas. It's important to assess each area individually to determine whether it meets the criteria for public urban green space. The assessment process involved analysing aerial imagery. Also, we used only UGS larger than 0,5 ha (Browning et al., 2024). We did not use the Urban Greenspace layer from the Urban Atlas, as a comparison revealed that these polygon layers are too generalised. Instead, we used network analysis to identify residential buildings from which it is possible to reach a park within 300 metres.

3.5 Evaluation of the fulfilment of the rule

The resulting map (Fig. 8) represents the percentage fulfilment of the rule for each residential building in Olomouc. The resulting map can take values from 0 to 100%. If all 3 sub-rules were met, all the resulting values would be 100%. Each of the rules can only be a maximum of 33.3% of the final assessment. Examples of the calculation of the total fulfilment of the rules are shown in Appendix 8. Results are categorised using quantiles.

4. Results

4.1 Rule 3

One of the main objectives of this study was the creation of a general and transferable methodology for the 3-30-300 rule which could be further applicable (not only) in Czech cities. This key part is logically presented in section 3. Methods and data. The results were followed up by an analysis of the spatial distribution and the fulfilment of the 3-30-300 rule criteria using the example of the city of Olomouc. Each part of the rule is visualised on an individual map (Figs. 5–7), followed by a map of all the criteria using the example of the chosen city (Fig. 8).

Almost 97% of the residential buildings in Olomouc comply with rule 3 (Fig. 5). This rule was quite easily fulfilled because the average number of trees in the buffer of 30 metres from the building was over 25. The lowest number of trees is in the central historical part of the city as the development is very dense and there is no space for trees and other greenery due to the narrow street network. Trees in courtyards are more common. The fact that the city centre is a culturally protected zone also means there are fewer opportunities to plant trees, at least well-established ones. Outside the historical centre, the number of trees in some peripheral areas is low, mainly due to the proximity of arable land or industrial development. In places of new development, the lower number of trees detected may be because there are small juvenile trees which are not captured by the Tree Detection tool.

4.2 Rule 30

None of the residential buildings achieved the criterion of having at least 30% of canopy cover in a neighbourhood, not even those in the immediate vicinity of the parks, where the maximum of 20.2% was only achieved by a few buildings (Fig. 6). This is because park vegetation is not only made up of trees, but mainly by low greenery, which is not included in the 3-30-300 rule. There are also wide roads near the parks that reduce the possible number of trees in the neighbourhood. The lowest values for this part of the rule are in the southeastern part of Olomouc, which is mostly industrial. Alternatively, the western part of Olomouc, where planned housing estates are located, has a higher canopy cover value (between 10–19.9%). These housing estates were built in the 60s and 70s and the trees there are older and well-established. In the historical centre, the canopy cover is low (less than 10%) as there is not a high number of trees (see Results of the rule 3).

4.3 Rule 300

Almost a quarter of the residential buildings in Olomouc have access to the nearest park within 300 m or less (Fig. 7). In the case of this rule we can observe spatial differences caused by the uneven distribution of the parks in the city. Rule 300 is fulfilled in areas that were planned, which means areas of green space created for the purpose of recreation as in the case of planned housing estates. Regarding the historical centre, the establishment of the surrounding parks is related to the demolition of the fortifications. In the case of newer developments (since the 90s), it is evident that central green areas are no longer planned. Furthermore, longer distances (more than 1,500 metres) to the nearest park exist in the eastern part of Olomouc because of the high number of industrial buildings.

4.4 Evaluation of the fulfilment of the rule

The maximum value of the fulfilment of this rule is 87% (Fig. 8). In Olomouc, the 100% rule was not met, as 30% of canopy cover was not achieved anywhere. The best results were achieved mainly in the areas of the housing estates that were built during the socialist period. The built-up housing blocks near the parks around the city centre are in the highest category (75–87%). Among the areas with a low percentage of compliance with the rule is the south-eastern part of the city where there are more industrial buildings and almost no areas of urban greenery. The resulting map also shows the differences between the western and eastern parts of Olomouc. This difference can be caused by different historical developments, the eastern part being more industrial, with the dominant type of development being a built-up area of detached and terraced houses. In contrast, the western part is more planned and the typical type of built-up area is a housing estate.

Finally, we assess the fulfilment of the 3-30-300 rule in land use/land cover (LULC) classification based on the well-recognised concept of Local climate zones (Stewart & Oke, 2012). The mean

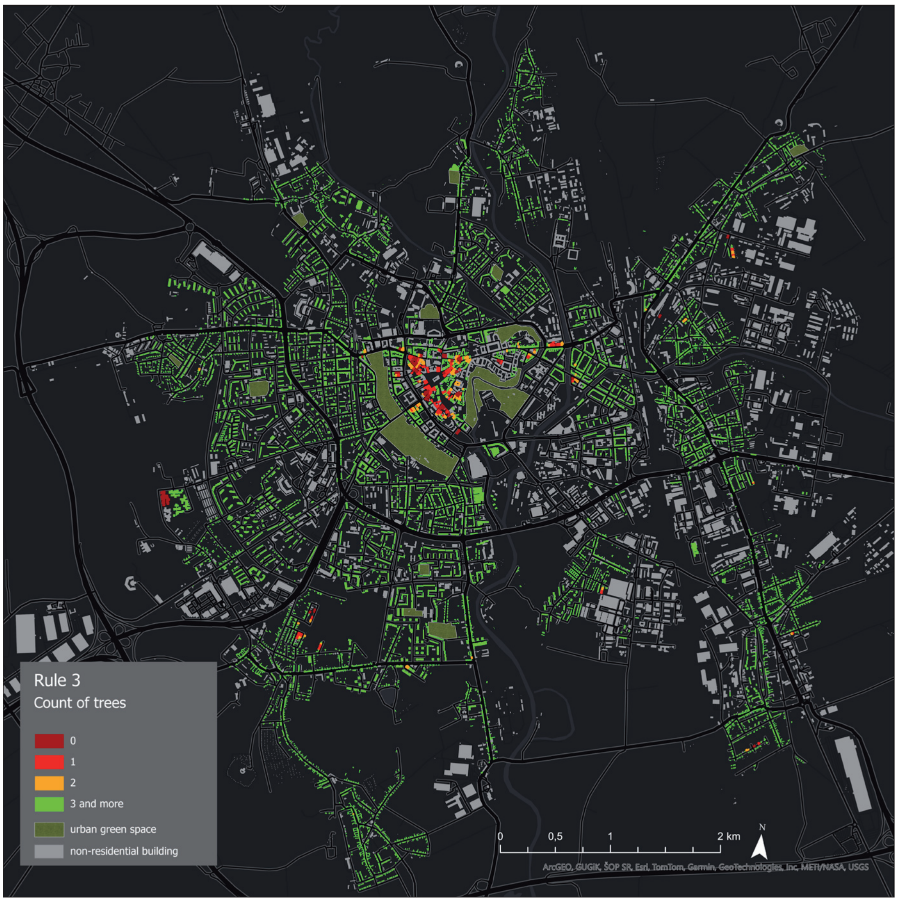

Fig. 5: Results of the rule 3 (case study: Olomouc)
Source: ČÚZK (2024b), authors' research and calculations

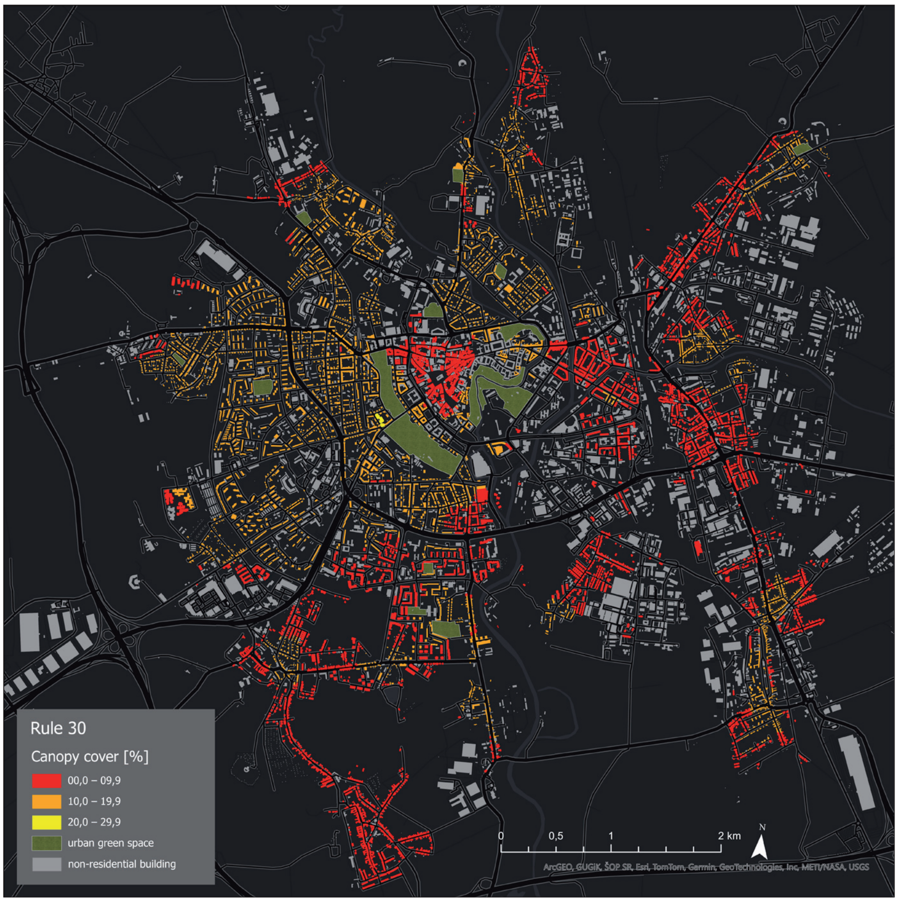

Fig. 6: Results of the rule 30 (case study: Olomouc)
Source: ČÚZK (2024b), authors' research and calculations

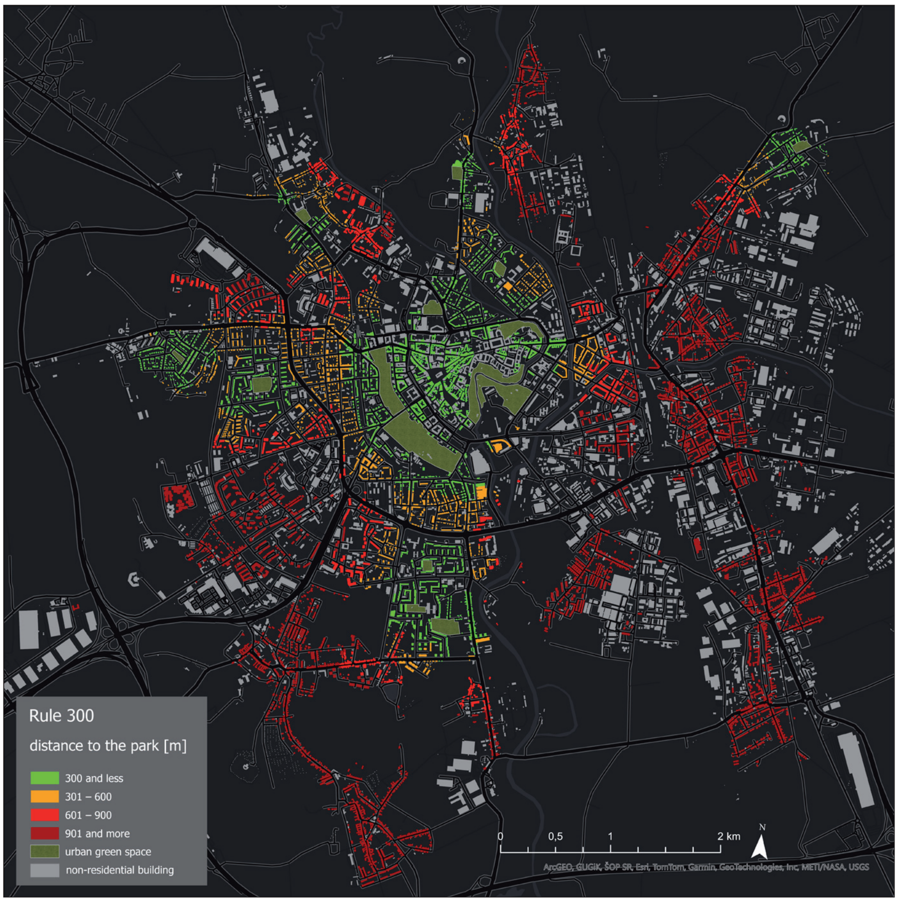

Fig. 7: Results of the rule 300 (case study: Olomouc)
Source: ČÚZK (2024b), authors' research and calculations

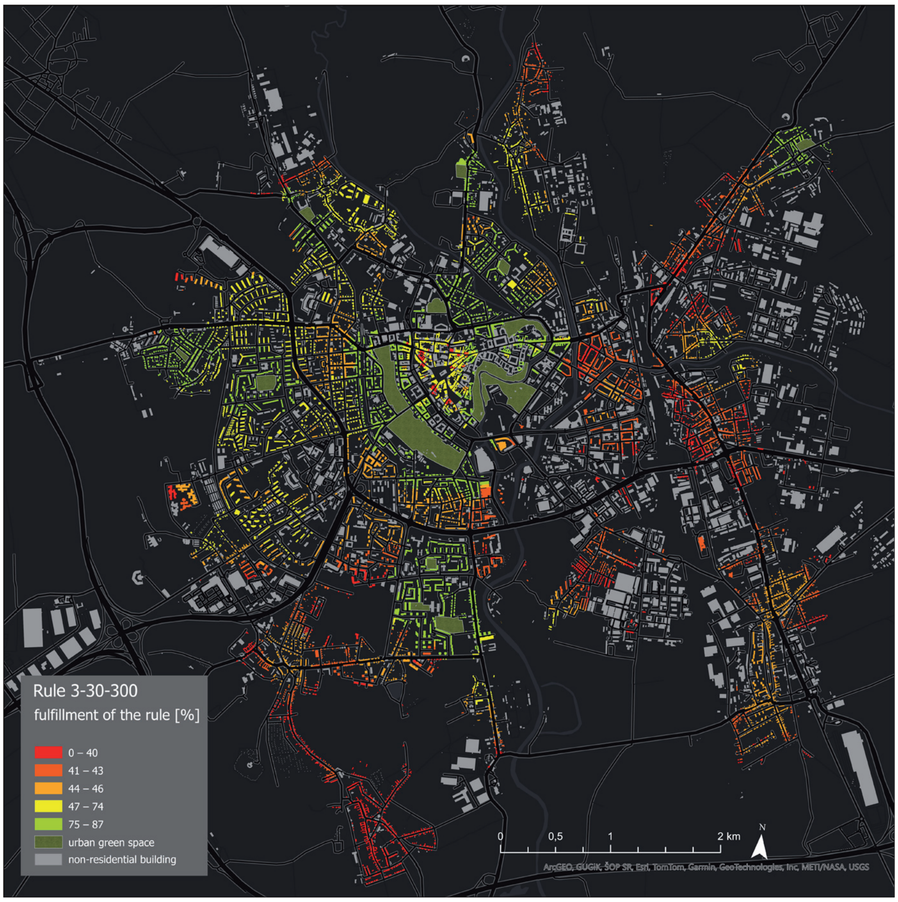

Fig. 8: Results of the fulfilment of the rule 3-30-300 (case study: Olomouc)
Source: ČÚZK (2024b), authors' research and calculations

value of the fulfilment of the 3-30-300 rule is calculated for each category of the Local climate zone (Fig. 9). Essentially, in areas of high population density of LCZ 2 (compact midrise) and LCZ 4 (open high-rise), the fulfilment of the rule is the greatest. In the case of LCZ 2, located in the city centre, it is particularly in Olomouc (which used to be a fortress town) that a substantial part of the households are located in the proximity of the central park ring (once areas behind the fortress). However, there is high intrazonal variability in the case of LCZ 2, as some households are still oriented towards urban squares with little or no greenery (the same is true for LCZ 5 open midrise). The good results for LCZ 4 confirm that several housing estates built under socialist planning generally provide good access to public greenery. On the other hand, in the case of LCZ 6 (open low-rise) and LCZ 9 (sparsely built), most of the greenery is in private gardens, which compromises the results. As expected, in the case of LCZ 8 (large low-rise) and LCZ 10 (heavy industry), the fulfilment of the rule is the lowest.

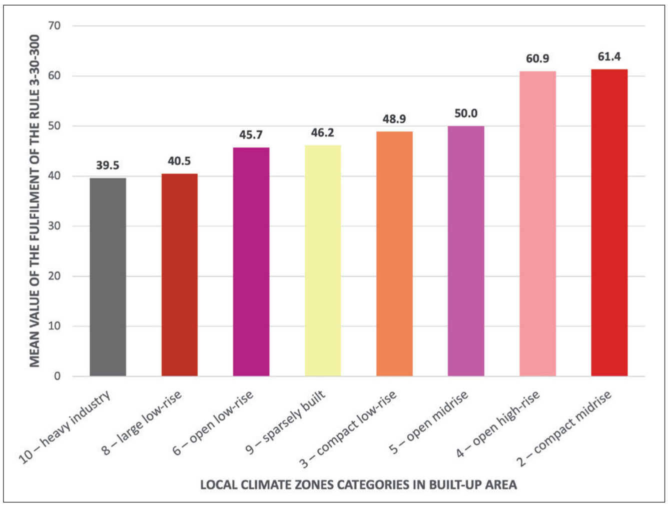

Fig. 9: Mean value of the fulfilment of the rule 3-30-300 for Local climate zone categories in built-up areas (Olomouc)
Source: Geletič & Lehnert (2016), authors' elaboration

5. Discussion

The 3-30-300 rule offers a standardised approach to evaluating the accessibility of urban greenery. One of its key advantages lies in its potential applicability across diverse geographic contexts. Introduced in 2021, the rule remains a relatively novel concept, with limited research available into its practical implementation (Konijnendijk, 2021).

This study represents one of the pioneering attempts to apply the 3-30-300 rule in a real-world urban environment. By focusing on the Czech city of Olomouc, it addresses both the practical and theoretical challenges that must be resolved to enable the broader, more universal application of the rule. The methodology outlined in this study aims to establish a replicable procedure for applying the 3-30-300 rule, with the goal of supporting its future standardisation in Czech cities and beyond.

5.1 Discussion of the results

Regarding visible 3 trees were achieved for almost all houses in Olomouc (using the method of counting the trees in a buffer zone). In a case study of Xiamen city (Zheng et al., 2024) being able to see three trees from the window was achieved for more than 79% of respondents. Another case study from Florida (Koeser et al., 2024) was based on questionnaires, and only more than a third of the respondents had three trees visible from their window. Nevertheless, the criterion for the visibility of the number of trees could be set a bit more strictly (see also section 5.2.).

In the case of the Olomouc, the value of 30% of canopy cover was unable to be reached. This part is difficult to achieve. The strategic document Master Plan for Barcelona's Trees from 2017 to 2037 (Guitard et al., 2017) has the goal of increasing the number of trees in the urban area of Barcelona to 30%. In the Chinese city Xiamen only 3.55% of residential buildings were fully compliant with the rule (Zheng et al., 2024). Another case study was created for the cities of Rheden, Velp, and Dieren in the Netherlands, and the analysis is captured through a web application and can be submitted to visualise the individual components of the rule (Rheden, 2024). In this case, it can be seen that the 30% coverage condition is met only in the peripheral parts of the city. The direct comparison of the results is not possible due to the utilisation of disparate approaches. In the case of Xiamen, a 500 m buffer for Rule 30 was employed; however, this is based on national sources (specifically, 500 m in this case is based on the Ministry of Housing and Urban-Rural Development of the People's Republic of China (Zheng et al., 2024)). In contrast, our analysis employs a 300-metre buffer, which is based on Rule 300. Furthermore, an alternative set of input data is provided for the purpose of analysis. Just because the goal of rule 30 was not achieved in many buildings does not mean that the rule is inappropriate. The rule is a challenge for cities to improve the accessibility of green infrastructure. If we calculated the percentage of canopy cover plus grassland, the value of canopy cover would be greater (see also 5.2).

Distances to the nearest park (300 rule) within the urban area of Olomouc varied according to administrative districts, with some districts having more accessible parks than others. In Xiamen, 11% of the buildings have access to the nearest park which is less than 300 m away (Zheng et al., 2024). In the case study of Florida, it is about 37% (Koeser et al., 2024). An important aspect of the analysis is the definition of urban green space and its input layer. Without knowledge of local conditions, it is difficult to decide which green areas meet all the parameters to be a public urban space in which leisure time can be actively spent. Some line-spacing green infrastructure in a city (e.g. green space around the river) can be also used for recreation if it does not meet the criteria to be a park. Based on these results, it can be discussed whether the components of the rule are set appropriately (see also section 5.2).

5.2 Limitations and application of the study and the rule

First, it is important to carefully choose a suitable data source for the analysis. In this study, we employed aerial data pertaining to the entire territory of the Czech Republic in order to examine rule 3 and rule 30. For the delineation of rule 300, we utilise cadastral plans, which are developed by each larger municipality. A potential limitation in this regard pertains to the inconsistent year of creation of these plans, necessitating cross-references with orthophotos, for instance. In another case study dedicated to the application of the rule, the analysis that was carried out in Xiamen City (Zheng et al., 2024) relied on satellite-based Google Earth data and the calculation of Fractional Vegetation Cover based on NDVI. However, the parameters for the rule themselves are different from those used in the analysis of Czech cities, and do not include the use of deep learning tools. However, similarly to Zheng et al. (2024), following the principles for the application of the rule, we also use only freely available data, which makes the rule suitable for a wide range of users such as urban planners, engineers, politicians and the engaged public.

Regarding the rule '3 trees' visible from a window, based on the analyses of the overlaps of trees and buildings, our analyses employ the criteria of 30 metres distance from a building, which is also in accord with Groeninzicht (2022). Data high resolution from remote sensing (Azeez et al., 2021; Katz et al., 2020; Seiferling et al., 2017) and Lidar data (Kakoulaki et al., 2021) are not free in the desired resolution, so we used aerial orthophoto data for the analyses.

The orthophoto data are free available for the entire area of the Czech Republic. As it is problematic to use generalised tools for tree detection (Weinstein et al., 2019), individual tree segmentation algorithms employing deep learning tools were proposed. The use of deep learning tools is always associated with a certain error rate. As for the error rate, we partially eliminated it by choosing an appropriate level of confidence, based on research in sample areas. Errors occur with the calculation of trees within larger clusters when using this tool. In the case of a cluster where there are 7 trees, 4 to 9 trees can be detected by using a deep learning tool. This error was not eliminated in this analysis, as it does not have a major impact on the overall result. The visibility of the trees differs from each window, depending on which direction the windows are facing and the height of the floor in a building. These differences are significant and it is not possible to uniformly decide whether a given building meets the rule, therefore the trees in the buffer zone are counted. The complexity of the determination and the effort to determine the visibility of 3 trees from a window as objectively as possible contrasts with the fact that basing the determination on the specific number '3' is not strongly supported by scientific evidence, but was chosen to connect with the numbers 30 and 300 from the communication perspective (Konijnendijk, 2023).

Regarding rule 30, the definition of the area of a neighbourhood in which canopy cover is counted was problematic. The authors of the 3-30-300 guideline should communicate this more specifically and we believe that this is a task for further research. Nevertheless, rule 30 is better supported by scientific evidence. The 30% canopy cover improves the quality of people's sleep and overall health (Astell-Burt & Feng, 2019). Even the results of the study by Iungman et al. (2023) say that achieving 30% canopy cover will decrease deaths from heat stress by a third. Ziter et al. (2019) also mention that a better cooling effect is achieved at 40% canopy cover. However, if we elaborate the effects of greenery on climate, it is obvious that the effect of greenery on climate differs with the type of greenery, the position of greenery (trees) in the built-up environment, and the building pattern/character of development (Bowler et al., 2010; Geletič et al., 2023). There also remain doubts in terms of assessing the accessibility of green space; the fact that only canopy cover is counted here, not other vegetation, may be problematic in this case. If grassland and other lower vegetation were also counted, 30% vegetation cover would be achieved in more cases. Browning et al. (2024) recommend using 30% green vegetation in arid areas. The results of Krüger et al. (2017) and Lehnert et al. (2021) suggest that in respect to weather and seasons, in some parts of the world even low vegetation can create positive environmental stimuli for citizens.

If we were to include 'parks' in the Rule 300 category, as publicly accessible areas of urban wilderness that perform park functions to a limited extent, the result would certainly be significantly more positive regarding a better overall balance for the entire city. However, from a methodological point of view, this step is problematic, if only because each town would need to have officially designated publicly accessible areas of urban wilderness, which would theoretically make the green areas somewhat regulated as there would be some demands on them in terms of human use, and thus they would lose their wilderness character. Access to green space can be also limited by some physical barriers (e.g. railways, highways). In the Olomouc case study, there is a spatial differentiation in green space accessibility in each part of the city. Some parts are at higher risk in terms of thermal stress. This is connected to the historical development of the city, especially in the industrial parts that were rebuilt into residential areas without the components of adaptive capacity (Shartova et al., 2024). Urban green space prevails in certain types of development; in Olomouc these are mainly in the socialist-built housing estates. Specifically found on the outskirts of the city, the function of UGS can be performed by green spaces that are not classified as UGS.

Concerning the novelty of the 3-30-300 rule, theoretical-methodical limits related to the relatively unchanging and egalitarian character of the rules are expected. They should be noted and discussed further. We understand and support the idea that the rule has to be generalised to a certain degree, easy to communicate and memorable to a wide spectrum of actors. However, concerning the experience we gained in our study, we criticise the fact that rule '3' is not more convincingly based on scientific evidence, and there is no more detailed guidance for the calculation of particular rules. It is also apparent that 3-30-300 thresholds can be considered by specialists from various disciplines dealing with urban greenery as very rigid when used to consider the environmental quality of life in particular cities. Furthermore, as indicated by Daniel and Jirmus (2023), green elements combined with green space should be located in a targeted and uniform manner in correlation with the needs of residents, and these could differ among neighbourhoods and cities. Therefore, the implementation of the 3-30-300 rule may be criticised by those who prefer free urban development and they may label the rule as leftist to socialist (it is probably not a coincidence that planned developments from the socialist era, with inherent public green spaces, achieve comparatively better results in Olomouc than modern housing estates with private greenery). In contrast, the 3-30-300 rule guarantees a kind of backbone mechanism for the improvement of public spaces in any city to improve social tensions. Therefore, based on our recent experience with the 3-30-300 rule we believe that it can efficiently serve as an essential primary analysis for comparing the accessibility of greenery in a city and among cities, and it should be further developed. Based on the above mentioned facts we suggest that in the future the 3-30-300 rule could be assessed in an index based on relative values (i.e. the extent to which the rules are met), which would also reduce the pressure on their strictly set threshold and allow appropriate values for this index to be set for different types of development/world regions.

Regarding the application of the 3-30-300 rule, it can serve local policymakers in the preparation of land use plans. The rule not only assesses the availability of green space, but also the spatial distribution of green space in the city, and not only for recreational purposes. At the same time, the utilisation of this rule facilitates the identification of locations that are deficient in green space. Given that freely available data are utilised, Czech local policymakers should already have access to these data; however, they do not have guidance (or even a tool) on how to perform the application of the 3-30-300 rule. In certain countries, notably those in northern Europe, the 3-30-300 rule has been incorporated into spatial planning. A notable example is the Yggdrasil project – The Living Nordic City (Konijnendijk et al., 2025). The potential exists for the creation of a guideline for the application of the 3-30-300 rule in Czech cities, following the example of the Yggdrasil project. In the Yggdrasil project, rule 3 is established using a buffer zone measuring approximately 25 metres. However, a 30-metre buffer zone was selected in this study, as it corresponds more closely to the built-up area in the Czech Republic. Rule 30 calculates again using a buffer zone, with the neighbourhood buffer chosen to be 500; however, in our analysis following the third component of the rule, we chose 300. In the case of the 300 rule, the Yggdrasil project uses remote sensing data in combination with Open Street maps. In contrast, our analysis proposes the utilisation of cadastral plans, which are recognised for their superior accuracy and capacity to identify high-quality green spaces.

6. Conclusion

This study is one of the first to employ an analysis of the newly proposed 3-30-300 rule in real urban environments. We found easily applicable and suitable approaches for using the rule and it was tested on the Central European city of Olomouc. In our case study, the threshold of 3 visible trees from a window was achieved in 97% of residential buildings, however the 30% canopy cover was not achieved in all cases. Distance to the nearest park depends on the type of development and the planned housing estates reached this threshold more easily than the industrial parts of the city. Rule 3 is generated by quantifying the trees (obtained by the deep learning tool) within a 30-metre buffer zone. For rule 30, the area of trees was considered, and the coverage in a 300 m buffer zone was counted following the third component of the rule. For rule 300, network analysis using access points was employed, and high-quality green spaces were selected using cadastral plans. Overall, our research shows that the 3-30-300 rule is a feasible method for measuring the availability of greenery in (Czech) cities. Our suggested method uses free public data and a deep learning tool so it can be easily used (not only) by local policymakers and is easily applicable to all buildings in a city. Without a doubt, the further development of the assessment of greenery in cities is important and is not just linked to climate change adaptation measures.

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Appendices

Appendix 1: Proportion of false negative and false positive objects in each sample area in interval of confidence 10–100
Source: Authors' research and calculations

Confidence interval		**10–100**		
Number of points	Trees detected	False positive	False negative	Error %
Detached houses	1,218	40	4	3.61
Terraced houses	617	26	2	4.54
Historical centre	153	32	2	22.22
Housing blocks	187	19	2	11.23
Street type	449	26	2	6.24
Housing estates	1,381	35	18	3.84

Appendix 2: Proportion of false negative and false positive objects in each sample area in interval of confidence 20–100
Source: Authors' research and calculations

Confidence interval		**20–100**		
Number of points	Trees detected	False positive	False negative	Error %
Detached houses	1,076	16	7	2.14
Terraced houses	528	10	3	2.46
Historical centre	91	5	2	7.69
Housing blocks	143	2	6	5.59
Street type	382	5	2	1.83
Housing estates	1,129	15	20	3.10

Appendix 3: Proportion of false negative and false positive objects in each sample area in interval of confidence 25–100
Source: Authors' research and calculations

Confidence interval		**25–100**		
Number of points	Trees detected	False positive	False negative	Error %
Detached houses	927	4	10	1.51
Terraced houses	439	5	12	3.87
Historical centre	76	2	1	3.95
Housing blocks	119	0	3	2.52
Street type	317	1	8	2.84
Housing estates	960	10	15	2.60

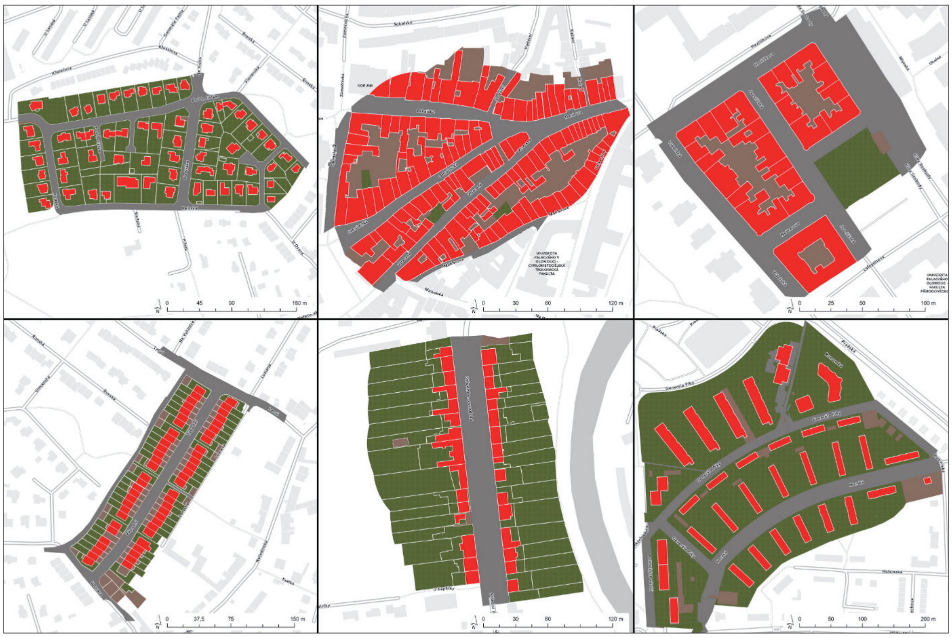
Appendix 4: Proportion of false negative and false positive objects in each sample area in interval of confidence 30–100
Source: Authors' research and calculations

Confidence interval		**30–100**		
Number of points	Trees detected	False positive	False negative	Error %
Detached houses	750	8	15	3.07
Terraced houses	349	3	18	6.02
Historical centre	63	0	5	7.94
Housing blocks	95	0	5	5.26
Street type	255	2	12	5.49
Housing estates	812	6	20	3.20

Appendix 5: Proportion of false negative and false positive objects in each sample area in interval of confidence 40–100
Source: Authors' research and calculations

Confidence interval		**40–100**		
Number of points	Trees detected	False positive	False negative	Error %
Detached houses	457	1	132	29.10
Terraced houses	192	0	65	33.85
Historical centre	41	0	19	46.34
Housing blocks	71	0	26	36.62
Street type	157	1	54	35.03
Housing estates	564	1	95	17.02

Appendix 6: Sample areas based on types of development in the Czech Republic, case of Olomouc
Source: ČÚZK (2024), authors' research and calculations



Appendix 7: Errors in different intervals of values of confidence in each sample area. Source: Authors' research and calculations

Type of development built-up area of	**Errors in different intervals of values of confidence (%)**				
	10–100	20–100	25–100	30–100	40–100
Detached houses	3.6	2.1	1.5	3.1	29.1
Terraced houses	4.5	2.5	3.9	6.0	33.9
Historical centre	22.2	7.7	3.9	7.9	46.3
Housing blocks	11.2	5.6	2.5	5.3	36.6
Street type	6.2	1.8	2.8	5.5	35.0
Housing estates	3.8	3.1	2.6	3.2	17.0
All types	8.6	3.8	2.9	5.2	33.0

Appendix 8: Examples of counting the fulfilment of the rule 3-30-300 Source: Authors' research and calculations

Rule 3	**Number of trees**	**Percentage of total score [%]**
	1	11.1
	3	33.3
Rule 30	**Canopy cover [%]**	**Percentage of total score [%]**
	10	10.001
	30	33.3
Rule 300	**Distance to the park [m]**	**Percentage of total score [%]**
	Less or equal than 300	33.3
	More than 300	0.0

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