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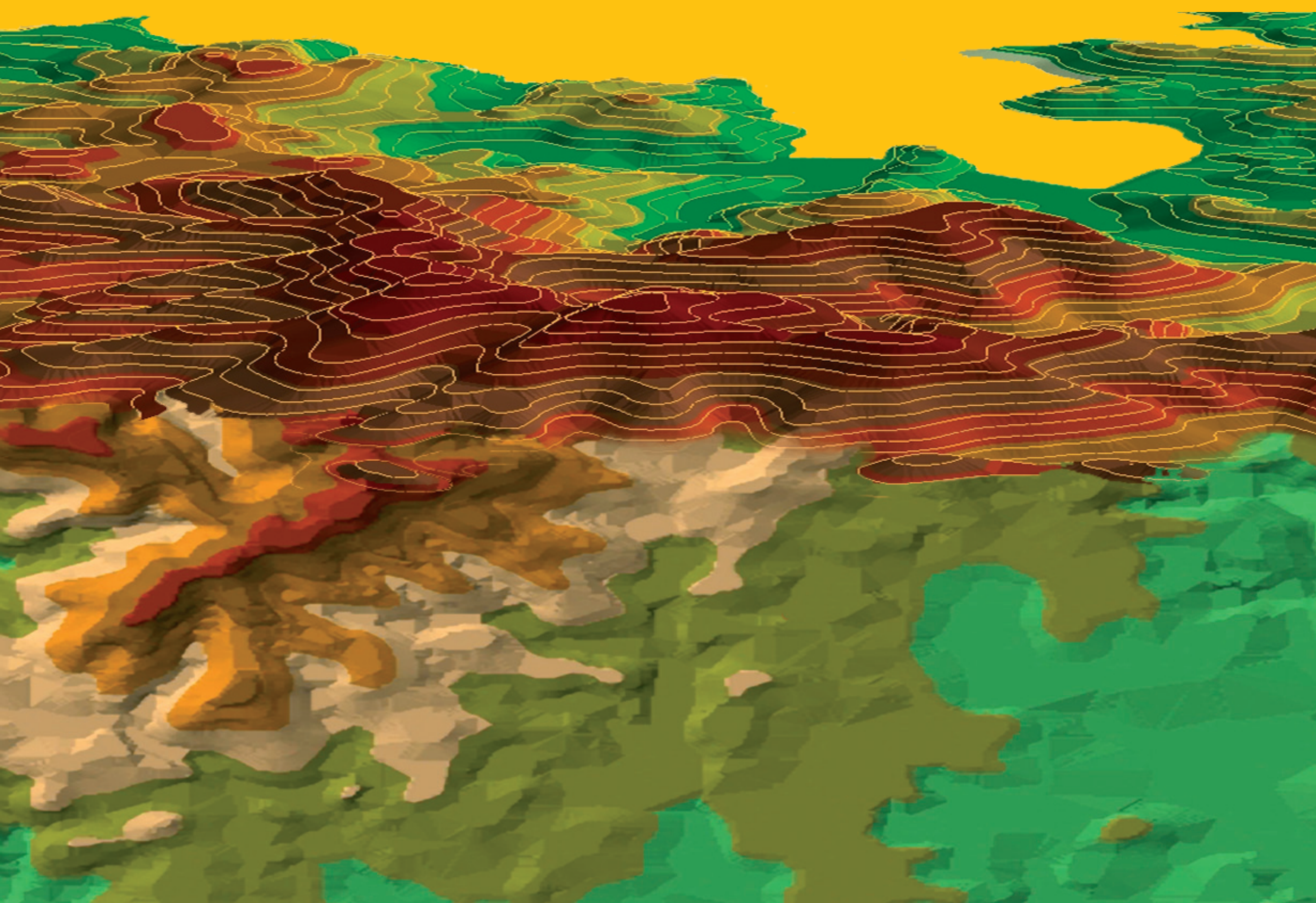

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Active commuting as a form of sustainable urban mobility: The case of the Brno Metropolitan Area

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Abstract

Environmentally friendly alternatives to motorised transport have recently become a topic of discussion among political representatives. To achieve sustainable urban mobility objectives, political discussions have focused on promoting cycling, walking and using public transport in cities. These modes of transportation are attractive ways of commuting to and from work for a portion of the population. In the literature, there is a growing interest in the phenomenon of active commuting. This paper examines the spatio-temporal patterns and practices of active commuting and evaluates their significance in the context of sustainable urban mobility. The empirical research is based on data obtained from a questionnaire survey and semistructured interviews conducted in 2023 in the Brno Metropolitan Area. Based on the data, three categories of active commuting were identified, namely pragmatic active commuting, physical active commuting, and combined active commuting, which differ in the implementation of different spatio-temporal practices. For the development of sustainable transport in the city, it is necessary to promote the construction of pedestrian and bicycle infrastructure, with the aim of making movement for pedestrians and cyclists more straightforward, efficient, and safer, including paying attention to actions leading to the embedding of this mode of transport in the wider societal context.

Keywords: *Active commuting, spatio-temporal practices, urban mobility, transport mode, Brno Metropolitan Area, physical activity*

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1. Introduction

In recent years, interest in environmentally friendly alternatives to motor transport has been growing. The current policies in many cities can be described as restricting car use and promoting public transport, cycling and walking (Buehler et al., 2017). This trend also applies to Brno (Czech Republic). Discussions at the level of political representation in Brno municipality are centred around promoting walking and cycling. To improve the transport accessibility of various locations in the city, the importance of public transport is also discussed. Strategy 2050 for Brno aims to increase the attractiveness and usage of sustainable modes of transport, thereby mitigating the adverse effects of transportation on urban life in the context of the entire Brno Metropolitan Area (StrategyForBrno, 2024).

One of the important components of urban mobility is commuting for work. The mode of transportation by which individuals get to work by walking, running, or cycling is most commonly referred to as 'active commuting' (Jones & Ogilvie, 2012, p. 22). Some researchers use the term 'active travel' (Saelens & Handy, 2008; Freeman et al., 2013) or 'active form of transport' (Shannon et al., 2006, p. 1) to express a type of movement involving walking, cycling and using public transport in combination with walking and cycling. Other studies label this movement as non-motorised transport (Rietveld, 2000; Saelens & Handy, 2008). The common element of these modes is the inclusion of physical activity during the journey and positive contribution to the natural environment. Active commuting can often be the most efficient mode of transport (Hansen & Nielsen, 2014).

The discourse surrounding sustainable urban transportation is also becoming increasingly prominent. Black (1996, p. 151) defined sustainable transportation as "satisfying current transport and mobility needs without compromising the ability of future generations to meet these needs". In this article, satisfying mobility needs can be understood as efficient movements from one place to another within an urban environment. Sustainability, in this meaning, balances the economic, social and environmental pillars (Litman, 2007; Silva et al., 2010). Sustainable transport contributes positively to the economic and social state without harming human health and the environment (Silva et al., 2010), where also the protection of natural resources belongs to one of the basic principles (Gudmundsson & Hojer, 1996). In addition to the term 'sustainable transport', the term 'sustainable mobility' is used to denote a wider understanding of mobility practices. Banister (2008) states that the sustainable mobility approach aims to reduce travel needs, encourage modal shift through the promotion of walking and cycling, shorten trip lengths, and encourage transport system efficiency. Sustainable mobility is related to a diverse transport system that offers travellers various modes, locations

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and pricing options. The various components of such transport system are well integrated, such as pedestrian and cycling access to transit (Litman, 2007). Walking, cycling, ridesharing, public transport, car-sharing and teleworking, as well as the creation of more walkable and transit-oriented communities, are all parts of improving the diversity of the transport system (Litman, 2007). Sustainable mobility characterises that all modes of transportation are considered in a hierarchy, with pedestrians and cyclists at the top and car users at the bottom (Banister, 2008).

To comprehend the significance of active commuting and functional sustainable planning in the urban environment, it is crucial to understand the spatio-temporal practices of individuals who actively transport themselves to and from work. This research employs a practice-based approach to examine the implementation of these practices. Its main objective is to provide answers to the following questions:

- What spatio-temporal practices are associated with active commuting?
- What are the implications of these existing spatio-temporal practices for sustainable urban mobility in the context of a practice-based approach?

This paper presents a comprehensive spatio-temporal analysis of active commuting in a selected area, identifying three distinct categories of active commuters based on semi-structured interviews. The results are contextualised within the framework of the objective to facilitate active commuting in the Brno Metropolitan Area. In the discussion, the article points out the key elements that are important to these efforts.

2. Theoretical background

2.1 Contextualising active mobility and active commuting

Active mobility encompasses various forms of walking, and as a result, a number of terms are used in the literature – destination walking (Alfonzo, 2005), purposive walking (Matos Wunderlich, 2008), utility walking (Pooley et al., 2014), destination-oriented walking and utilitarian walking (Saelens & Handy, 2008), active-transport walking (Millward et al., 2013). The meanings of these notions are distinct, as walking is a fundamental activity for humans and is not necessarily applicable to commuting. For the purposes of this article, it is essential to be aware of the concept of walking, which characterises movement from destination A to destination B, i.e. with the intention of reaching a specific destination. Previous research indicates that walking is done over very short distances. Millward et al. (2013) indicate the most common distance in the range of 0,2–0,4 km. These results are consistent with the findings of Scheiner (2010), Larsen et al. (2010); and also Rubín et al. (2015), who found that 90% of respondents who use active transportation to work walk within 30 minutes. Walking can be employed in a number of ways, independently or in conjunction with alternative modes of transport (Jones & Ogilvie, 2012). Sarker et al. (2020) showed that the shortest walk is connected with the way to the bus stop. Previous research demonstrated that the most prevalent walking distance to a bus stop is within a ten-minute radius (Sarker et al., 2020; Besser & Dannenberg, 2005; Lachapelle & Noland, 2012). A number of previous studies (Cerin et al., 2007; Wener & Evans, 2007; Villanueva et al., 2008; and Lachapelle & Noland, 2012) have shown an association between the use of public transport and an increased frequency of walking trips or higher levels of physical activity.

When considering a route, individuals often choose the most direct and shortest route (Tight et al., 2004), a decision partly influenced by limited in the amount of time they can spend moving from one place to another within a day (Marchetti, 1994). Many individuals see walking as a daily routine, often without conscious recognition of this activity. Seamon (1979), Wood et al. (2005), and Pooley et al. (2014) provide deeper insight into the habitual nature of walking, especially in conjunction with walking to work. An important factor that affects the decision to walk for transportation purposes is also the accessibility to the destination, which includes proximity of destinations (workplace), spatial distribution and land use mix within the given area (Saelens et al., 2003; Alfonzo, 2005; Cerin et al., 2007). Nevertheless, Hatamzadeh (2019) emphasises the role of the individual's experience and the individual's attitude toward walking. An individual's positive attitude towards walking increases their desire to walk. Desire to walk more means "whether a person wishes to increase his/her walking or not and could be considered as an intention for changing the travel behaviour in to a commute pattern in which the amount of walking would be more" (Hatamzadeh, 2019, p. 351). The choice of a walking route is also influenced by whether the route is part of a wider transport network providing good connections, crossing points, access to services, and fits the desires of individuals (Tight et al., 2004; Saelens et al., 2003).

The category of active mobility encompasses running. Despite its huge potential, running to work has received little attention so far. When authors incorporate running into their research, they often categorise it as a subfield of walking, such as Song et al. (2013). However, this topic is addressed in greater detail in the research of Cook (2021). His findings revealed that run-commuting is seasonal in nature, with the majority of individuals engaging in this practice one to two times per week. The average run time was found to be between 40 and 49 minutes. Another area of active commuting is cycling. In Poland, approximately 10% of respondents use cycling as a mode of transportation to work (Biernat et al., 2020). They also indicate that the average cycling time is under 20 minutes. The intensity and frequency of cycling use in the transport mix and in commuting decrease with increasing distance (Dickinson et al., 2003; Pucher & Buehler, 2006; Sears et al., 2012), with increasing travel time (Heinen et al., 2011), and with each additional kilometre (Heinen et al., 2013). On the other hand, Hansen and Nielsen (2014) identified a proportion of cyclists commuting longer distances (more than 5 km) and referred to them as long-distance commuter cyclists. Most respondents who commute by bicycle report cycling to work as a regular occurrence (Biernat et al., 2020). Nevertheless, previous research suggests that cycling to work has a seasonal trend with higher frequency in summer (Heinen et al., 2011; Sears et al., 2012; Hansen & Nielsen, 2014). Bergström and Magnusson (2003) highlight the differences in cycling behaviour and distinguish between winter cyclists, summer-only cyclists and infrequent cyclists.

As evidenced by previous research, active commuting can be viewed from the viewpoint of the pragmatic mode of mobility, typically employed for shorter journeys, but some individuals who walk (see Pooley et al., 2014), run (Cook, 2021) or cycle (see Heinen et al., 2011; Biernat et al., 2020) to work extend their journeys due to physical benefits and positive impact on an individual's health (see Oja et al., 1998; Rafiemanzelat et al., 2017).

2.2 Practice theory perspective on commuting

Practice theory provides a valuable framework for understanding commuting behaviours and sustainable transportation (Iyanna et al., 2019; Scheurenbrand et al., 2018). Reckwitz (2002) defines a practice as a routinised type of behaviour that involves interconnected bodily activities, mental activities, use of objects, specific knowledge, and emotional states. Practices are, in his perception, viewed as a collective phenomenon, representing shared ways of doing and understanding within a social group. Reckwitz (2002) highlights that practices encompass not just the physical actions but also the meanings, norms, and interpretations associated with those actions. They are embedded in broader social and cultural contexts, which provide them with specific significance and value. According to Shove et al. (2012), practices are constituted as bundles of interrelated elements. These elements include material components, competencies and meanings, which are interconnected and collectively enable the existence of a particular practice.

In this regard, commuting is a complex social practice shaped by materials, meanings, and competencies, requiring tactical negotiation of these factors (Guell et al., 2012). Iyanna et al. (2019) claim that meanings play a dominant role in shaping commuting practices, with competencies and materials integrated to address these meanings. As they demonstrated with the example of public transport, it can be associated with a social stigma that is culturally unacceptable (socio-cultural meanings). Some individuals may perceive it as a means of achieving freedom and independence (symbolic meanings), whereas others may view it as an inconvenient mode of transportation without physical discomfort (personal meanings). In the context of discussing practices, Watson (2012) posits that it is of significant importance to note the interconnected and interdependent nature of practices. This suggests that the implementation of one practice may have an impact on the outcome of another practice. Spurling et al. (2013) argue that practices are part of larger systems. In research, it is important to consider the broader system of practices, as the observed patterns of commuting behaviour may not be directly linked to transport policy but rather to the location of children's educational institutions. For that reason, Heisserer and Rau (2017) highlight the limitations of an individualistic approach to mobility research, which tends to focus on individuals, actors and their motives. They argue that commuting is linked to numerous other areas of social life and demonstrate that it is influenced by a range of factors, including material (infrastructure, availability of transport, etc.), social (the need to combine trips to get children to school, etc.) and political (laws and regulations) conditions. The practice-based approach was also used in some previous studies dealing with similar topics, Larsen (2018) outlines a practice-based approach to understanding long-distance commuter cycling in Denmark, and Cass and Faulconbridge (2016) used this approach in their study focused on the transition from automobile commuting to bus- and cycle-commuting.

3. Research design and methods

This study has been carried out in the Brno Metropolitan Area. The Brno Metropolitan Area is made up of 184 municipalities with a total population of approximately 700,000 inhabitants. Brno, as a central city, is the second largest city in the Czech Republic. The city was chosen because of its progressive, post-socialist character and the steady growth of its population. Walking and cycling in cities is becoming a more widely discussed topic in the Central European region, including Brno. Brno has a great tradition of using public transport, the use of which, in combination with walking, provides optimal conditions for research. Furthermore, it was found that there is a lack of research in this area on similar themes.

The study is based on a mixed-research design, with the analysis comprising information from a questionnaire survey and semi-structured interviews. The data obtained from the questionnaire survey provides a framework for qualitative analysis, as it reveals the fundamental characteristics of active commuting. The insights into spatio-temporal behaviour were greatly expanded by the information obtained from semi-structured interviews. The questionnaire survey was conducted electronically between September 2023 and December 2023. A total of 495 respondents (290 females and 205 males) provided responses. People were contacted through social networks (Facebook, X, Instagram, Reddit and LinkedIn) and websites related to Brno. The respondents were provided with a unique link, which they could utilise to access the survey. In the case of Facebook and Reddit, the link was shared in the public groups of the City of Brno, the city districts and the groups of individual municipalities. Furthermore, the link was posted in thematic groups focused on cycling, for example, "Brno na kole" ("Brno on bike"). This approach was taken in order to reach as many people as possible. On the X and LinkedIn platforms, the link was used to publish on a private account with a request to reshare. With regard to the municipalities situated in the hinterland of Brno, the selection process was based on a random approach. The objective was to ensure a relatively even distribution of the selected municipalities across the metropolitan region. Around 70% of the respondents reside in Brno, while the remaining 30% live in municipalities within the Brno Metropolitan Area. The questionnaire focused on individuals who walk or cycle all the way to or from work or use a combination of these modes with public transport. Individuals who only walk or cycle part of the journey and use public transport for the rest were also included in the study. The proportion of responses from the category of individuals walking and cycling is approximately equal. More specifically, 195 respondents reported walking the entire journey to work, 210 reported cycling the entire journey to work, and 90 reported combining active commuting with public transport during the journey to work. The age range and level of education were not predetermined. The questions concerned the spatio-temporal features of work-related mobility, specifically individuals' daily movements to and from work. The questionnaire was structured into a few segments, such as the journey to work and the journey from work. In cases where public transport was used, segments were defined as journeys from home to the public transport stop, from the public transport to work, and any walking errands between public transport trips, depending on the number of transfers. This data was complemented with information on motivations, seasonality and other contextual information.

Interviews with communication partners were performed simultaneously during this research period. The interviews were pre-structured, but the communication partners had the ability to alter the structure through their answers significantly. The main purpose of the semi-structured interview was to provide in-depth information on the topic that a questionnaire survey would not allow. Therefore, the specific spatio-temporal practices of individuals were investigated. Four types of communication partners were determined as an important for the qualitative analysis. The first group consisted of individuals who walked to or from work (1), the second group comprised individuals cycling to or from work (2), the third group involved runners to or from work (3), and the fourth group included individuals who combined either walking, running or cycling with public transport within the same journey to or from work (4). The individual was required to commute a few days a week using these modes of transport, but not necessarily every day. This research did not include other modes of transport, such as scooters, as part of the commute to work. Our analysis and local surveys showed that these modes are almost negligible in this region. To address the research question, a total of 22 semistructured interviews were included in the analysis (Tab. 1). The number of interviews conducted corresponds to the theoretical saturation in each of the four groups studied. Communication partners were recruited via social networks and various online groups that bring together runners, cyclists, walkers and platforms such as BrnoNaKole and others. A post was inserted into these groups, offering the opportunity for individuals to participate in research that specified the criteria for their involvement. Individuals who expressed interest were then randomly approached. The snowball method was also partly used.

The sample consists of 16 out of 22 communication partners residing in Brno. The youngest interviewee is 22 years old, and the oldest is 55. All interviews were recorded, transcribed and further analysed. All recordings were made with the consent of

Nickname (gender)	Age	Place of residence	Place of employment	Mode of transport
Martin (M)	29	Brno	Brno	walking
Tereza (F)	25	Brno	Brno	walking
Adéla (F)	55	Brno	Brno	walking
Jakub (M)	42	Brno	Brno	walking
Kateřina (F)	38	Kuřim	Brno	walking
Tomáš (M)	48	Brno	Brno	walking
Aneta (F)	41	Zbýšov	Brno	cycling
Hana (F)	45	Brno	Brno	cycling
Radoslav (M)	33	Brno	Brno	cycling
Miroslav (M)	38	Brno	Brno	cycling
Otakar (M)	42	Tišnov	Brno	cycling
Luboš (M)	36	Česká	Brno	cycling
Daniel (M)	22	Brno	Brno	cycling
David (M)	23	Brno	Brno	cycling
Pavel (M)	38	Rajhrad	Brno	walking/public transport
Eliška (F)	30	Brno	Brno	walking/public transport
Jan (M)	28	Brno	Brno	walking/public transport
Kamila (F)	44	Brno	Brno	walking/public transport
Robert (M)	26	Brno	Brno	walking/public transport
Lucie (F)	25	Brno	Brno	running
Radim (M)	36	Šlapanice	Brno	running
Markéta (F)	51	Brno	Brno	running

Tab. 1: An overview of communication partners
Source: Author's survey

the participants. The average length of the interviews is 48 min. A qualitative analysis was performed using a coding technique. Coding was carried out in successive stages, involving three levels of coding: open, axial and selective (according to the methodology of Hendl (2005). Open coding consisted of the initial labelling of words, sentences, and parts of texts in conversations. This was followed by axial coding, which entailed further reading and searching for motives, strategies, and reasons in relation to the theory. The process of selective coding was characterised by the definition of supporting themes in which certain codes are always grouped. To illustrate, during the open coding stage, a number of codes were generated, including 'simplicity', 'directness', 'shortest path', and 'fastest'. These were subsequently categorised as "simple movement A → B" following further reading and analysis, which included the use of various tools such as the Code Co-Occurrence Table and Networks. This led to the creation of the pragmatic way of active commuting. In the final stage of the analysis, three categories of active commuting subsequently emerged from the dozens of codes: pragmatic, physical active and combined active commuting. Each category can be assigned a number of specific codes that are typical for them. The typical range of such codes is between 20 and 40 per category.

4. Statistical data on active commuting

4.1 Time perspective of active commuting

The act of walking to work can be classified into two principal categories: either as the sole mode of transportation for the entire journey or in conjunction with the utilisation of public transportation. Walking data shows that the shortest walking trips are those to a public station. Of those who walk directly, four-fifths of respondents take up to 10 minutes to get from home to the public station, adding that two-fifths take up to 5 minutes. The journey may take longer if any other activities are related to the journey from home to the public station. The most commonly reported intervals were 6 to 10 minutes or 11 to 15 minutes. The walking time interval for the subsequent segment, from the public station to work, was found to be the same. Walking the entire journey to work is characterised by slightly longer distances. Over three-fifths of participants typically walk to work within a 15-minute timeframe, with more than half of this group reporting a commuting time of between 5 and 10 minutes. Additionally, 10% of respondents reported a commuting time of over 25 minutes (see Fig. 1). Obviously, the time duration of walking on the way to work observed in this study is consistent with the findings of previous research conducted by Scheiner (2010), Larsen et al. (2010), and Millward et al. (2013), although they reported the distance in metric units. Cycling to work is typical over longer distances. In the case of using a bicycle to work, three-quarters of individuals commute to work for a duration ranging from 11 to 30 minutes. Almost 20% of those questioned reported a commute longer than 30 minutes, and 3% reported a commute longer than an hour. These values are slightly higher than those found in a previous study conducted in Poland by Biernat et al. (2020).

The results indicate that the commute to work is typically shorter than the commute from work, regardless of whether it involves walking, cycling or a combination of these modes of transportation. Regarding combination walking with public transport, the travel times are higher by 5 minutes for those making a direct journey from work. If individuals engage in additional activities on their way home from work, their journeys become significantly longer. In such a situation, two-fifths of people take more than 20 minutes to travel from work to their first public station. On the final segment of the journey from the public station to home, walking times are shorter but also higher. According to our results, commuters mostly complete this segment within 15 minutes. For respondents who walk the entire journey home, approximately one-third of individuals take up to 10 minutes, while another one-third take more than 20 minutes for a direct journey. If additional activities are included, the journey takes longer, with over 50% of respondents taking more than 30 minutes. In relation to cycling, more than 50% of the respondents indicated that their commute from work to home takes between 31 and 60 minutes. Furthermore, nearly a quarter of the respondents have a commute from work to home that takes over an hour if it is not a direct route (see Fig. 2). It can be concluded that cycling is associated with the longest commuting times, both when travelling to and from work. The observed commuting times values for these types of active commuting to and from work correspond to the times reported in the research by Rubín et al. (2015).

4.2 The structure of journeys

In addition to the observation of longer journeys on the way home, certain similarities were also discovered. The morning commute is typically direct for all forms of active commuting

Fig. 1: Commuting time of active form of transport to work in case of direct journey (left) and in case of journey with stops (right). Even if some individuals typically (most often) complete a journey in a direct manner, if they undertake a journey with intermediate stops in at least some instances, they were also queried about the time taken
Source: Author's survey

Fig. 2: Commuting time of active form of transport from work in case of direct journey (left) and in case of journey with stops (right). Even if some individuals typically (most often) complete a journey in a direct manner, if they undertake a journey with intermediate stops in at least some instances, they were also queried about the time taken
Source: Author's survey

explored. In the case of a combination of walking with public transport, 90% of individuals walk directly from their homes to the public station and then continue directly to work. Of those who include other activities in these trip segments (home → work), 80% stop at stores for refreshments. The remaining percentage consists of stops at schools or daycares with children or leisure stops related to sports, such as going to the gym. The results are not significantly divergent from those observed for walking and cycling. However, the greatest dominance of direct journeys to work was observed among cyclists.

4.3 Daily, weekly and annual pattern

Walking and cycling have been observed to have some seasonality. Increased intensity was registered during the summer period, with peaks occurring in May and June. Subsequently, there is a decrease in commuting frequency in July and August, followed by an increase in September. Conversely, a higher decrease during the winter period was registered, especially for cycling. On the other hand, combining walking with public transportation during one journey appears to be a year-round activity. Differences in the frequency of commuting within the week were also identified. Walking and cycling to/from work is only registered on certain commuting days. The most commonly cited reasons for switching to an alternative mode of transportation to/from work were adverse weather, other obligations in private or professional life (such as a meeting or session) incompatible with walking or cycling, or actual mood. One-third of individuals who engage in cycling to work travel to work only every second or third journey. The frequency of using walking to work is slightly higher. Furthermore, it is important to note that differences exist within the year. One-fifth of the respondents reported walking entirely to work in only one direction on some days, either to work or home from work. Combining walking with public transport during one journey is typically used regularly on workdays with no clearly identifiable distribution across days.

The results of the questionnaires indicated that respondents who combined walking with public transport during one journey exhibited a distinct behavioural pattern with regard to departure time strategy. The time at which individuals leave their homes for work is influenced not only by factors such as working hours but also by the public transport system. Approximately half of the respondents stated that they set off at a specific time to catch the same public transport service that runs at the same time every day. Regarding the afternoon commute, the public transport system is less influential as a pacemaker when more than three-quarters of individuals leave work at a different time each day, making this spatio-temporal behaviour similar to individuals with characteristic physical active commuting. This makes the journey from work much more flexible in terms of time.

4.4 Spatial perspective of active commuting

It is also important to note the significant spatial fragmentation involved in walking the route home from work. The results of the questionnaire survey indicate that 60% of individuals do not follow the same route daily. It hints that journeys from work have become much more complicated and varied. An even lower percentage was observed for individuals who cycle to work, with as many as 45% of cyclists taking different routes on their return journey. This discrepancy is also because each way of active commuting is associated with specific motivations. For almost 80% of respondents, cycling to work is a form of physical activity. Additionally, 90% of the participants reported that it provides mental relaxation and rest. Individuals who choose this type of commuting often intentionally extend their journey from work and seek out new routes to take each time.

5. Specific commuting practices of active commuting

The analysis of the semi-structured interviews reveals the existence of three distinct categories of active commuting: pragmatic, physical active, and combined (Fig. 3). From the perspective of spatio-temporal analysis, it is significant to note that the three categories of commuting entail the utilisation of distinct spatio-temporal practices by individuals. All three types of active commuting represent certain specific behaviours in time and space and may occur simultaneously in the same individual but in different situations and contexts.

5.1 Pragmatic active commuting

One type of active commuting is pragmatic active commuting. The category of pragmatic commuting comprises practices that can be framed as 'efficient daily walking over short distances' and 'efficient destination cycling'. A fundamental attribute of pragmatic active commuting is a mode of transportation based on the motivation to reach the destination as easily and quickly as possible. One frequent explanation mentioned by communication partners for this spatio-temporal behaviour is the limited amount of time available for commuting. The basic principle of pragmatic active commuting is to get from point A (individual's home) to point B (individual's workplace) and vice versa.

5.1.1 Efficient daily walking over short distances

This spatio-temporal practice was observed in Martin, Adéla, Tereza, Jakub and Kateřina, whose walking journey to and from work can be labelled straightforward. As Martin says: "There is no reason to stop anywhere in the morning". Besides the individual motivation of commuters, the reduced frequency of stops for commuters walking to their destination may be attributed to the fact that these walking routes often pass through parks and housing estates, which are not conventional service locations. Therefore, those walking have limited opportunities to stop somewhere. The statements of the communication partners indicate that if commuting to work involves a stop, it is done in close proximity to the daily route. For instance, Adéla and Jakub mentioned rare stops at a bakery, small grocery store or café. However, these stops are typically en route. Therefore, communication partners do not significantly deviate from their planned route. This practice is carried out along the same, predefined, learned routes. All communication partners confirmed that their current walking route results from evolution and previous experience with other alternatives. The current route gives attributes such as most efficient, most pleasant, shortest, and only possible. Adéla stressed that "the important factor is the time". In addition to spatial characteristics, temporal consistency was also found. For the individuals interviewed, a consistent time of day of departure is typical. However, there were variations in arrival and departure times among the individuals studied. Adéla departs home as early as 6:30 AM and returns at 3:00 PM, while Tomáš heads home after 5:30 PM. These findings align with the temporal fragmentation of commuting (see Gorný, 2024).

The category of pragmatic commuting includes walking the entire journey. From the semi-structured interviews, it can be concluded that this type of active commuting is chosen as a mode of transport when individuals need to travel from home to work on a route that is not covered by public transport and where using public transport would result in increased travel time or a detour. This study validates previous research findings on the impact of environment on walking characteristics, albeit in a marginally distinct context:

> "If I was to take the tram from Zoologická to Svratecká (…) It takes 5 minutes to get to the next stop and 3 minutes to wait for the tram. So that would take 8 minutes, then the tram ride would

take 4 minutes. The journey to the office would take 16 minutes compared to 20 minutes on foot. The difference is too small. I rather walk." (Martin)

5.1.2 Efficient destination cycling

Another spatio-temporal practice that falls under the category of pragmatic active commuting is 'destination cycling'. This practice can be characterised as a quick and straightforward commute, similar to walking, but over longer distances. In this study, communication partners, such as Aneta, Hana, Miroslav, Luboš and Radoslav, implement this particular type of commuting behaviour in the morning as they travel to their place of work. The rationale provided is that there is no compelling reason for them to extend the journey; they simply commute to their place of work:

"When I started, I used to ride along the river because that route is nicer, but when you go to work, it's a few extra kilometres. So if you can go that way, if you're coming from work and want to go for a ride, you can go any way you want, but I take the shortest route for the vast majority of my morning rides." (Luboš)

Pragmatic active commutes can thus be characterised by the following spatio-temporal patterns: place of home → place of work and place of work → place of home.

5.2 Physical active commuting

An additional category of active commuting may be defined as physical active commuting, whereby the journey to work is undertaken with the intention of engaging in sporting activity. This type of commuting involves spatio-temporal practices such as 'after-work cycling' and 'run-commuting'.

5.2.1 After-work cycling

The rationale behind the delineation of after-work cycling is that the journey from the workplace often comprises a longer period of travel than is necessary. Communication partners who realise this spatio-temporal practice mentioned the longest trip durations in the context of journeys that are part of commuting. Some active commuters take their journeys from work as an opportunity for sport and physical exercise for the body. The aim of such motivated individuals is to implement the longest routes possible, depending on the time available to them. For instance, according to Hana and Aneta, such a journey takes them more than 5–6 hours in the longest cases. These findings are in contradiction with the pragmatic active commuting discussed above:

"If possible, I take a longer route through Adamov, Kuřim, or other villages near Brno (…) It takes around 4 hours. So I leave the faculty at 3:00 PM and return at 8:00 or 9:00 PM. However, this requires extra time. So this year, I only did it for 2–3 hours, covering a distance of maybe 30–40 km." (Hana)

However, the length of the journey is affected by the season, with the biggest factor being the length of daylight. During winter, when daylight hours are shorter, communication partners reported shorter journeys compared to summer. In a semi-structured interview, Aneta stated that she rides up to 15 different routes. Similar commuting behaviour with multiple route options was mentioned by Radoslav, Miroslav, Otakar, Luboš, Hana, David and Daniel. Especially Daniel exhibits remarkable spatio-temporal behaviour. Despite living only a few minutes away from work, he drives along the surrounding streets on his way home to get some exercise. The time it takes is indifferent to him:

"I can actually go back and forth between Antonínská–Semilasso [tram stations] with the fact that my favourite section in Brno is Slovanské náměstí – it's the biggest roundabout in Brno and I can do as many circuits as I want." (Daniel)

The findings from this research are in line with Hansen and Nielsen (2014), who concluded that the main motive for commuting a long distance on a bicycle is physical exercise and stress relief. These reasons were repeated across the interviews we conducted. At the same time, all communication partners who implemented this spatio-temporal pattern expressed a positive attitude towards cycling, even in their free time. Chen and Chen (2013) and Heesch et al. (2015) found that individuals who cycle for leisure prefer cycling routes with attractions along the way, whereas those who cycle for transportation choose the shortest route. Our research has shown that there is a hybrid, i.e. individuals who behave as if they are cycling for leisure when travelling from work to home.

5.2.2 Run-commuting

A further spatio-temporal pattern that has been documented in our study is the phenomenon of running to or from the workplace. This process has previously been designated as 'run commuting' (Cook, 2021). In our research, running to or from work concerns Lucie, Radim and Markéta. Amongst these communication partners, the shared element of the 'run-commuting' practice is the running of routes with the specific goal of achieving a certain level of athletic performance. Lucie is engaged in a training regimen for a half marathon, which results in a variable running routine on a daily basis. The duration, velocity, and terrain of her runs, as well as the routes she traverses, exhibit considerable variation. On some days, she runs a basic route without timing, simply for the pleasure of the activity. On other days, she attempts to run the same route at a specific time. On occasion, she stops at the athletic stadium to engage in interval training. Markéta also referenced comparable spatio-temporal behaviour, noting that, as part of her training regimen, she occasionally diverges from her established route to incorporate hilly terrain:

"On Monday, I run the core route; on Tuesday and Thursday, I take it as training, so on Tuesday, I run through the athletics stadium and on Thursday, I run circles in Lužánky Park." (Lucie)

While Lucie and Markéta run only in the direction from work to home, Radim runs only to work. This is a consequence of the other activities and responsibilities that they undertake, for example, Radim is required to spend the afternoon with his son. However, their statements agree that incorporating running into their daily commute enables the integration of two activities into one and thus affords them more leisure time after they get home from work. The statements of the communication partners also demonstrate that run-commuting is not a daily occurrence. Lucie runs once a week, Radim and Markéta three times a week, with all of them emphasising the significance of rest days.

To sum up, using the example of run-commuting practices, we can thus confirm the results of Larsen (2018), indicating that commuting can be an effective form of training. In such circumstances, the route taken by communication partners between their place of employment and their place of work is not the shortest available option. Rather, it is extended for a number of reasons, which is the essence of physical active commuting.

5.3 Combined active commuting

In addition to the pragmatic and physical active commuting, the statements of communication partners also suggest the existence of another form of active commuting, which may be referred to as combined active commuting. From the semi-structured interviews, three basic spatio-temporal patterns have been identified in the context of combined active commuting. The first spatio-temporal practice represents simple combined commuting, the second includes walking between two journeys made by public transport during commuting from work, which has been labelled as 'in-between walking on the journey home'. The third spatio-temporal practice that arose from the semi-structured interviews has been denoted as 'walking errands before getting on public transport'.

5.3.1 Simple combined commuting

Simple commuting refers to commuting behaviour characterised by walking to a public transport stop without making any stops, then taking transport and walking again to the destination without making any stops. This spatio-temporal practice is carried out with varying frequency by all communication partners who stated that they sometimes use public transport when travelling. This spatial practice was observed both on the way to work and on the way home.

5.3.2 In-between walking

In-between walking is a characteristic feature of Kamila and Eliška's commute. It should be noted that this walking errand is not a regular daily journey for these communication partners. A characteristic feature of this walking segment is its irregularity within the week. Eliška implements this type of walking into her commuting twice a week. Moreover, she states that the form of such walking has several variations, with the main distinction being in its length. Even for Kamila, this spatio-temporal behaviour is not an everyday occurrence. Semi-structured interviews indicate that in-between walking is performed due to the necessity of arranging or purchasing something. Frequent stops on this journey include shops, mail-order houses, restaurants, and offices. Thus, one form of spatio-temporal pattern typical for combined active commuting can be described as follows: being at work → riding public transport → in-between-walking → riding public transport → walking home.

5.3.3 Walking errands before getting on public transport

The second spatio-temporal pattern can be denoted as "walking errands before getting on public transport". It has been found that some communication partners carry out walking errands during the first segment of the journey home from work, which means immediately when they get off work. This spatio-temporal pattern, mentioned by Kamila, Jan, Pavel and Robert, is also characterised by irregularity and does not occur daily. For Jan, this walking journey, in combination with time in the shop, takes one to two hours, which means he usually arrives home between 6 and 7 PM. Pavel adjusts his work schedule accordingly. If he needs to run errands in town, he finishes work early to catch the next bus. However, if he has plans to do an activity with friends later in the day, he stays at work longer and this pattern is then observed in the later hours. The responses of the communication partners showed that during the final segment of the journey, i.e. from the last public transport stop towards home, none of the communication partners mentioned any stops; the aim is always to get home as quickly as possible, which is in line with the results of the questionnaire survey. Thus, the second significant observed spatio-temporal pattern of this type of active commuting takes the form of being at work → walking in the city → riding public transport → walking home.

The two spatio-temporal patterns are linked to a common element – the variability in the selection of public transport stops. In relation to commuting from work, it was observed that communication partners do not arrive at the same public transport stop after their walking errands. Individuals mentioned various options for continuing their journey home and pointed to the option of choosing the public transport stops they needed to reach. Therefore, the length of these walking errands and their positioning in space can vary greatly:

> "But if I want to go to another shop, I take a different bus to a different station, and there I walk a little bit; I don't take the 12 anymore, but I go straight to the 4 to the main station." (Eliška)

5.4 Common features of pragmatic and physical active commuting

Although the various forms of active commuting differ from each other, some similarities can be found between pragmatic and physical active commuting. These two types of commuting

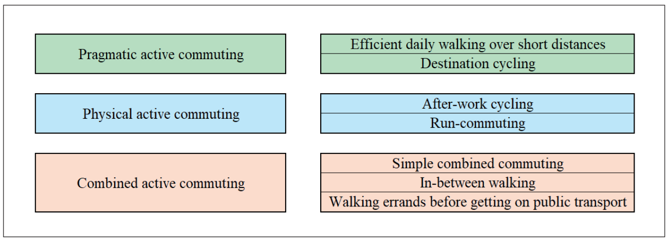

Fig. 3: Types of active commuting (left) and its corresponding spatio-temporal practices (right)
Source: Author's conceptualisation

are characterised by seasonal rhythm. Using the example of communication partners, it can be noted that Tereza and Jakub, who typically walk the entire route to work, alter their mode of transportation during the winter period due to the darkness because of passing their route through unilluminated areas. Jakub does not want to walk through the fields and forests on the outskirts of the town. Tereza avoids poorly lit corners near her place of work. Both of them replace walking with utilising public transport:

> "During winter, I like taking the tram because there is less daylight. On Vídeňská Street, there is a square where some people with drug addiction can be found. It's not recommended to go there alone, especially in the early evening when there are no lights." (Tereza)

The connection between the environment and weather is another crucial aspect that demands attention. Communication partners have a tendency to refrain from walking the entire journey due to muddy terrain caused by rainy weather. This is an example of Jakub's situation, who walks on partially unpaved roads when commuting to work and resorts to public transportation in rainy weather. On the contrary, in the case of combined active commuting, communication partners were unable to express any seasonal rhythm.

6. Discussion

This research pointed out that transport planners should take into consideration the existence of more forms of active commuting, which vary in terms of the implementation of different spatio-temporal practices by individuals. In other words, it differs in temporal and spatial features of the journeys to and from work. On the one hand, some forms of active commuting involve simple and straightforward movement, while on the other hand, some forms of active commuting involve intentionally prolonging journeys (Fig. 4). With regard to these results, this study contributes to the aforementioned existing literature by demonstrating that active commuting encompasses more than merely 'short-distance commuting'. Spatio-temporal practices that typify physical active commuting are defined by longer journeys. It can be concluded that they are comparable in length to car journeys (e.g. Schwanen et al., 2003). These journeys are intentionally extended, with typical durations exceeding 30 minutes, regardless of whether they are undertaken on a bicycle or in the form of a run. In exceptional cases, the duration of physical active commuting in the form of after-work cycling or run-commuting may extend to an hour or more. Both individuals who use bicycles and those who run to work extend their commuting journey due to the efficiency gained from combining transportation and physical activity into a one-time slot. For cyclists, an increase in time was observed solely on the return journey from work. In contrast, for runners, the increase was noted on both the outward and return journeys.

From a spatial perspective, the journeys made from workplaces are more diverse than those made to workplaces. In a significant number of cases, the route taken from the workplace does not coincide with the route taken on the previous journey, nor is it the

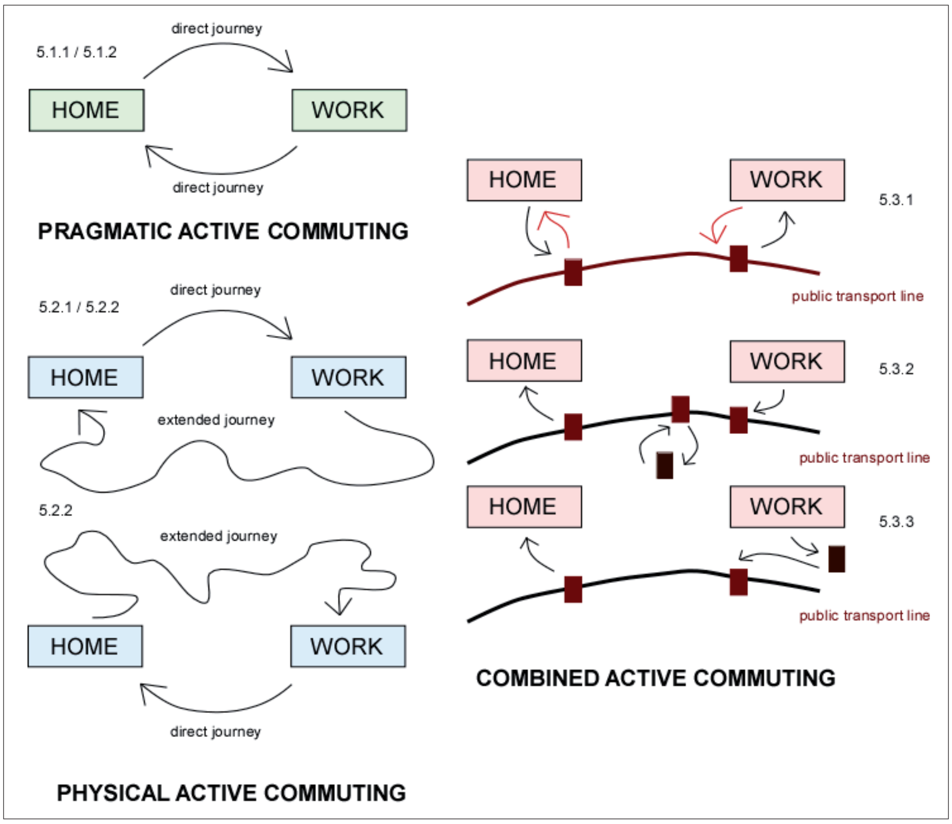

Fig. 4: Visualisation of observed spatio-temporal practices
Source: Author's conceptualisation

same route in the morning. It should be noted, however, that in the physically active commuting category, a higher proportion of respondents implemented a variety of options in their journeys.

Consistent with previous research (Humpel et al., 2002; Lee & Moudon, 2004), it has been confirmed that paying attention to accessibility, in this case, accessibility to work, is crucial. The efficiency of the journey taken from home to work determines whether one decides to walk or bike to work. The accessibility also refers to the accessibility of public transport stations and the overall efficiency of the public transport system in the city. An important supporting factor is the speed of travel compared to alternative transport options. Thus, the time efficiency of each mode of transport must be considered. If walking (or cycling) the entire journey is more time-efficient than combining walking with public transport, the individual would rather walk the whole journey. Our results are in line with Rietveld (2000), which emphasises the greater potential for the use of non-motorised modes where competing modes of transportation are slower. In this regard, the impact of land use on active commuting, or more broadly on the selection of transportation modes, is evident. Prior research has demonstrated the influence of density, diversity and design on travel demand (Cervero & Kockelman, 1997). Subsequent research has extended this to encompass destination accessibility and distance to transit (Ewing & Cervero, 2010). Badland and Schofield (2005) highlighted the existence of positive correlations between physical activity levels and mixed land use, density, and street connectivity. Based on the interviews, it is evident that street connectivity, destination accessibility, and distance to transit should be given particular emphasis to increase active commuting. Consequently, the priority for policy implementation should be the construction of convenient and safe sidewalks and bicycle paths that effectively connect residential areas of cities to employment locations.

The integration of active commuting into the city's intermodal transportation system appears to be a complex issue as there was observed a contradictory relationship between types of active commuting and public transport. While walking is combined with public transport in a single journey, the same cannot be said for cycling and running to work. Although Kosmidis and Müller-Eie (2024) demonstrated that the bike-transit combination is used as a mode of transportation in countries such as the Netherlands and China, our research came up with different results. We found that when individuals choose to cycle to work, they cycle the entire journey. This finding is, on the contrary, consistent with Kaplan et al. (2016). The main reason lies in the inefficiency of a journey that would be made partly by bicycle and partly by public transport. The same incompatibility with public transport applies to the use of private bicycles, and also to the use of shared bicycles (van Marsbergen et al., 2022). It should be added that in the case of the Brno Metropolitan Area, 'public transport' means mainly using tram, bus and trolleybus. Research conducted by Martens (2004) found that faster modes of public transport, such as trains, are more closely linked to the cycle-transport mix. Therefore, results from individual regions can vary quite significantly.

However, our research has shown that some individuals integrate walking with public transport during the same journey, as well as alternating between walking and public transport on different days. Combining walking with public transport is also important for those who prefer to walk the entire journey, e.g. in case of bad weather, important meetings, or time pressure, and also for runners who only run one way. Therefore, the other priority for policy implementation should be ensuring efficient public transport.

We agree with Scheurenbrand et al. (2018) that policy interventions need to take a holistic, practice-based approach that addresses the alignment of materials, competencies, and meanings across the bundle of related practices. While intervention in material elements (e.g. investment in infrastructure) is necessary, it is also crucial to consider changing cultural meanings and social norms (Watson, 2012). Besides public institutions, it is also an incentive for the private sector and companies, e.g. to encourage more sporting challenges in commuting. However, as Cass and Faulconbridge (2016) have observed, it is necessary to consider the broader social structures that shape these activities, including the location of shops, health centres, and the increasingly complex spatio-temporal patterns of youth leisure activities, as these activities are also sequenced with commuting.

7. Conclusions

Active commuting encompasses different modes of transportation. This research focused in detail on spatio-temporal practices of active commuting as an important aspect of sustainable urban mobility. The study revealed the significance of distinguishing between three types of active commuting: pragmatic active, physical active and combined active commuting. Each type has unique characteristics and spatio-temporal practices that should be considered.

Combined active commuting is characterised by shortest distances and year-round implementation. The journey to work is generally direct, with more frequent stops on the journey home. Typical spatio-temporal practices include 'simple combined commuting', 'in-between-walking' and 'walking errands before getting on transport'. It can also be described by the commuting patterns taking the forms of being at work → walking in the city → riding public transport → walking home and being at work → riding public transport → in-between-walking → riding public transport → walking home. Timing to public transport departures is a particular feature used by half of the respondents. Pragmatic active commuting represents straightforward, short, uncomplicated and direct journeys in order to get from point A to point B, as maximum time efficiency and effectiveness are the main decision-making variables for the commute. Within pragmatic active commuting, spatio-temporal practices named 'efficient walking over short distances' and 'destination cycling' have been observed. In other words, this type of active commuting characterises commuting patterns taking the forms of place of home → place of work and place of work → place of home. Physical active commuting is represented by longer journeys, which are motivated by the implementation of sports activity into the commute. Our analysis identified two spatio-temporal practices that were particularly prevalent within physical active commuting: 'after-work cycling' and 'run-commuting'. These practices exhibit considerable variation, which gives rise to a range of spatial movements on a daily basis. As with pragmatic active commuting, it is typical of physical active commuting for there to be seasonal patterns with a peak in the summer months. It is important to note that the observed commuting practices are highly context-specific. This research presents results from the Brno Metropolitan Area. It does not preclude the existence of other practices that may coexist within these three types of active commuting, and which did not occur in this area due to infrastructural, cultural or other differences.

All of these types of active commuting can be categorised as a form of sustainable urban mobility. To enhance its relevance, measures should be taken to facilitate the implementation of these three forms of active transportation. Further research should focus on opportunities to use other active commuting alternatives, such as scooters and shared bikes, and assess the differences that may arise within the metropolitan area or smaller cities. At the same time, the issue of run-commuting, which represents a relatively under-researched area within the field of active commuting, is deserving of further attention. Support for urban running infrastructure is dependent on accurate data on commuting intensity and the spatio-temporal behaviour of runners.

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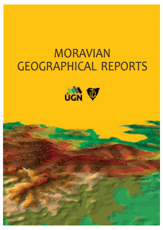

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The stability of cooperation in the context of cross-border cooperation: The example of Poland's borderlands

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Abstract

The objective of this paper was to conceptualise the issue of cooperation stability in research on cross-border cooperation. On this basis, regularities related to selected aspects of the stability of cross-border cooperation were identified using the example of the Polish border regions. The analysis was based on a complex review of the Interreg, ETC, ENPI, and ENI cross-border cooperation programmes implemented in the Polish border regions between 2007–2013 and 2014–2020, taking into account both internal and external EU borders. The study covered a total of 1,577 projects realised between 2007–2013 and 2014–2020 by more than 4,500 beneficiaries, comprising 2,307 organisations. A survey of these organisations was also conducted. The resulting analysis helped to identify the relative stability of partner types and the thematic scope and spatial dimension of cross-border cooperation, while at the same time revealing a lack of stability in the organisational dimension. In addition, the study showed that the initiation and subsequent maintenance of cross-border relationships are the result of a complex process, in which many factors co-exist simultaneously, whereas the break-up of cooperation can be the product of individual factors.

Keywords: *Cooperation stability, cross-border cooperation, Interreg projects, borderland, Poland*

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1. Introduction

Due to its complexity and multifaceted nature, the issue of borderland development represents a significant research challenge (Wassenberg et al., 2015). Cross-border cooperation, including the implementation of cross-border cooperation programmes, plays a special role in the process of regional and local development. These projects are not the only form of cooperation across borders. However, they are often its most important manifestation (in its actuality, and not just the declarative form of cooperation) and the starting point for the development of other cross-border activities of both a formal and informal nature.

In the European Union (EU), cross-border cooperation projects are largely the result of the established cross-border cooperation policy, which is an important element of the cohesion (Perkmann, 1999) and neighbourhood policy[1]. In view of its articulated aspiration to permanently eliminate existing barriers at the borders, adversely affecting the socio-economic space, the issue of stability of cooperation seems particularly important in this context, as it could play a fundamental role in the development of border areas and in overcoming their peripherality in the long term.

It is worth noting that the phenomenon of stability in the cross-border cooperation implemented within the framework of cooperation programmes financed by the EU has thus far been rarely studied, especially in the form of complex, in-depth, and dynamic research. This is probably due to the complexity and ambiguity of the concept of stability itself (especially as it emerges in the field of social sciences), as well as the tendency to study this phenomenon in relation to the cooperation between people, economic entities, or international powers, which rarely takes into account the border context. Moreover, it is difficult to determine the extent to which the phenomenon of stability has a positive or negative impact on the shaping of cooperation.

The main objective of the study was to theoretically consider the possibility of including the issue of cooperation stability in research on cross-border cooperation, with the further goal of conceptualising such a research approach. On this basis, an empirical investigation identified certain regularities related to selected aspects of cross-border cooperation in the Polish borderlands. These regularities were associated with the organisations involved in cooperation, the thematic scope of the projects implemented, their spatial distribution, and the premises underlying the establishment, continuation, or termination of cooperation. This study covers the

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[1] The European Neighbourhood Policy was launched in 2007 with the aim of framing EU relations with those non-EU countries which are bordering the Union but not candidates for accession within a single policy instrument (Celata et al., 2016).

formal cooperation implemented within the framework of cross-border cooperation programmes co-financed by EU funds. Thus, it does not cover the whole range of cross-border cooperation (formal and informal), but concerns a very important aspect of this phenomenon, since, according to Perkmann (1999), Interreg programmes have been a long-standing source of funding for most cross-border cooperation initiatives.

2. Theoretical aspects of cooperation stability

2.1 Cross-border cooperation and its specific characteristics

Cross-border cooperation emerged and became popular as a common strategy for overcoming the divisive role of the border, with the aim of integrating border areas at the national level, but also, and perhaps more importantly, at the regional and local levels. Such cooperation influences the border area and can lead to the creation of cross-border regions stretching outward both sides of the border, which are characterised by strong links of various kinds at many levels, including specific ways of functioning on the part of local authorities, inhabitants, or businesses that reflect these changes in the 'territoriality of border areas' (Popescu, 2011). Cross-border cooperation is generally seen as a positive phenomenon for regional development and European integration (Svensson, 2021) and border region functioning (Böhm, 2023).

Due to its multifaceted character, the issue of cross-border cooperation and the development of border regions constitute an important, extensive, and interdisciplinary research topic (i.e. Brunet-Jailly, 2005; Jones, 2009; Popescu, 2011; Prokkola, 2019; Chilla & Lambracht, 2023). A significant strand of research on cooperation is devoted to the influence of borders on the development of border regions, including the factors that limit its negative effects (i.e. Evrard, 2022). Research emphasising the role of the border as a resource is also important (Sohn, 2014), including in the field of tourism (Timothy & Więckowski, 2023). Regarding these factors, various economic flows have been indicated as important in terms of shaping stability, prosperity, and territorial cohesion (Decoville & Durand, 2016). At the same time, many studies emphasise the specificity of border regions, which is reflected in the fact that even numerous and strong interactions do not necessarily lead to an increase in the convergence and degree of similarity of border regions (Topaloglou et al., 2005). Related to this is the problem of asymmetry of border areas in various socio-economic dimensions (Leimgruber, 2005; Dołzbłasz, 2015).

Taking into account the approach of Durand and Decoville (2020), the implementation of cross-border cooperation projects can be regarded as one of the key components of the process of cross-border integration. At the same time, it should be remembered that this process is complex and multifaceted and may manifest differently in individual borderlands. This is in line with the observation by Anderson and O'Dowd (1999) that every border region is unique, and borders and their roles often produce dissimilar meanings in individual countries (Paasi & Ferdoush, 2023). According to Durand and Decoville (2020), the essential components of this process include the functional dimension of cross-border integration (e.g. cross-border practices), the ideational dimension (e.g. the level of mutual social trust between border populations), and the institutional dimension (e.g. the involvement of stakeholders in cross-border cooperation projects). Thus, the study of cross-border cooperation projects implemented under the EU's cohesion policy falls under the third component mentioned above.

The studies conducted so far indicate that there is no single universal pattern governing cross-border cooperation development (Durand & Decoville, 2020) and its diversity (Kaucic & Sohn, 2022). The observed variety of factors that are relevant to the development of cross-border territories (e.g. formal-legal, cultural, economic, etc.) could, therefore, potentially influence different attitudes of organisations towards cross-border cooperation, including the motives for its establishment, further continuation, and perceived benefits or barriers to its implementation. Identifying these attitudes and motivations of organisations, therefore, seems important, as they can significantly alter the course of integration processes (Borges et al., 2022).

Moreover, it is worth noting that the nature of cross-border cooperation is such that it does not emerge overnight, but is instead the effect of long-term processes that are of an integrative and disintegrative nature (i.e. Blatter, 2004; Wassenberg et al., 2015). This confirms the viability of studying the phenomenon of cooperation stability from a longer-term perspective and its impact on cross-border cooperation, both in its positive and negative dimensions.

2.2 The issue of cooperation stability

According to Pena Suarez (2012), understanding the emergence and stability of cooperation is a central issue in many areas of both the natural and social sciences. As a result, studies on this topic have been carried out in several scientific disciplines (e.g. economics, management, psychology, political science, sociology, and biological sciences) and using a variety of quantitative and qualitative methods. At the same time, there is no single, generally accepted, or even well-established definition of cooperation stability in the literature. Among the existing studies on this topic, a very broad strand covers the behaviour of individuals and human groups, addressing, among other things, the propensity for interpersonal cooperation (Számadó et al., 2016; Reigstad et al., 2017), cooperation between scientists (Cainelli et al., 2012), psycho-economic reasons for making the decision to cooperate (Berger & Grüne, 2016), cooperation in the field of public goods (Fischbacher & Gächter, 2010; Lankau et al., 2012), and the role of evolutionary biology (Smith & Price, 1973; Taylor & Nowak, 2007). Another important strand of research is devoted to the analysis of the stability of company cooperation (i.e. Windsor, 2007; Hatak et al., 2015), cooperation in the field of R&D (i.e. Atallah, 2003; Zeng et al., 2017) as well as stability of cooperation between countries within the framework of organisations and international treaties (i.e. Langlois & Langlois, 2001; Baciu, 2020).

At the same time, the concept of stability is understood in very different ways. One of the pioneers in the study of cooperation stability was Axelrod (1984), who used game theory to show that it is largely determined by an unlimited number of interactions (i.e. the permanence of mutual relationships). This explains why the importance of subsequent interactions between the same partners becomes so high that the strategy of non-cooperation becomes unprofitable. In this context, the basis for cooperation is therefore the permanence of relationships. In contrast, an alternative approach was presented by Bendor and Swistak (1997), who proposed that stability refers to the ability of a given system to return to its initial state after a subtle disturbance. In this sense, the strength of stability is measured by the amount of disturbance it can withstand. It is worth noting that in the social science research, stability is often understood in the common sense of the relative permanence of different dimensions of cooperation over time (e.g. of the subject or the object of cooperation). Moreover, in many cases, the research in this area makes use of theoretical and empirical models based on game theory (i.e. Axelrod, 1984; Conlon, 2003; Nax et al., 2015).

The results of Axelrod's (1984) research show that the stability of cooperation, understood as its recurrence, is an integral condition for the development of cooperation itself. Thus, under the right conditions, stable cooperation can develop, even between antagonists. Particularly important from this point of view seems to be the research by Reigstad et al. (2017), which confirms the existence of a stable behavioural inclination towards prosociality (or the 'cooperative phenotype') and provides an argument for the relative stability of people's cooperative behaviour across countries and over time.

In studies of people's behaviour, Lankau et al. (2012) found that the temporal stability of preferences for the provision of public goods is highly dependent on the social environment. This is particularly true for people with the same identity, who show much higher levels of cooperation than those without such an identity. The willingness to cooperate can therefore be systematically increased by enhancing the perceived sense of belonging to the group with which one interacts. Similarly, a significant sense of identity has also been observed in the area of international cooperation between countries (Sommer et al., 2008). For instance, Jafroudi (2018) treats the stability of cooperation as the basis for the effectiveness of international policies implemented through interstate agreements. The most effective mechanisms available to prevent withdrawal from cooperation appear to be high exit barriers, such as those in the form of reputational damage, the implementation of countermeasures, or the use of dispute settlement measures. According to Gaudeul et al. (2017), if the exit barriers are low, this poses a threat to group coherence, as it encourages units to attach more importance to their own short-lived particular interests than to strengthening the goals of the community.

Despite the extensive literature on the subject, as Reigstad et al. (2017) have pointed out, relatively little research has been devoted to verifying the extent to which the willingness to cooperate is stable under different conditions and over time. An example of such an approach would be Cainelli et al.'s (2012) network analysis of publication cooperation among scientists in different time periods, or Reigstad et al.'s (2017) analysis of changes over time in the willingness to cooperate among people in different countries of the world.

2.3 Stability of cross-border cooperation

In relation to borderlands, the issue of stability has mainly been raised in the field of border stability within political geography and geopolitics (i.e. Berg & Kim, 2016; Carter & Poast, 2017). Although cross-border comparative studies have been conducted in various border regions (i.e. Dołzbłasz & Raczyk 2015), research on the stability of cooperation is poorly represented in the literature. Meanwhile, as Wassenberg et al. (2015) noted, the rules of cooperation at the EU level are organised in a similar way for all territorially interested partners, which creates favourable conditions for dynamic studies.

Studies that have focused on the issue of stability have been most often concerned with cross-border infrastructure networks or the cross-border management of environmental resources (mostly water resources, such as rivers with a cross-border character; see Dinar et al., 2019). In general, there have been no in-depth analyses of the stability of cooperation in joint cross-border projects implemented by public organisations and the non-governmental sector. Moreover, there have been relatively few studies on the issue of long-lasting partnerships in the cross-border cooperation projects (i.e. Szmigiel-Rawska, 2013) or factors influencing continuation of cooperation (Raczyk & Dołzbłasz, 2022). Nevertheless, it is worth noting that selected aspects of cooperation stability have appeared in some border studies, specifically in relation to trust and the ease of implementing activities (van Houtum, 1998; Capello et al., 2018), the sustainability of the institutional system (i.e. Blatter, 2004; Biot, 2013), the importance of stable conditions (Karppi, 2001), and the long-term effects of cooperation (Scott, 2003).

In response to a number of phenomena that negatively affect the development of border regions and cross-border cooperation (e.g. geopolitical problems or the COVID-19 pandemic), the concept of resilience has recently become popular in border studies (Prokkola, 2019; Böhm, 2021; Hippe et al., 2022). In general, the concept refers to the ability to accommodate shocks and to move back to pre-shock conditions (Prokkola, 2019). Therefore, this approach seems to clearly correspond to the definition of stability proposed by Bendor and Swistak (1997). However, adopting such a perspective to study the phenomenon of stability limits it only to emergency (crisis) situations, which does not fully reflect its essence, as understood by Axelrod (1984), who appropriately focused on the study of the relevant relationships (within successive, consecutive interactions).

Given the lack of clear definitions of the stability of cross-border cooperation in the literature, for the purposes of this study, the authors have adopted an approach that is an adaptation of the concept presented by Axelrod (1984) to the field of border studies. It should be noted, however, that this concept should be understood as a starting point for studies on cooperation in the broader sense. The starting point for defining the stability of cross-border cooperation was the EU cross-border cooperation policy, which is an important component of the EU's cohesion policy. In this case, to fully understand cross-border relations, it is important to know who cooperates with whom, what happens within this cooperation, and where it takes place. These categories are closely related, and their joint analysis increases the effectiveness of the analyses of cross-border cooperation (Chilla & Lambracht, 2023). Thus, in this understanding, stability refers to the existence of stable spatial structures, stable subjects of cooperation, and stable consortia implementing joint cross-border projects.

On this basis, it has been assumed in this article that the stability of cross-border cooperation is to be understood as a certain level of recurrence of cooperation, which is itself to be understood, however, not only in terms of the category of recurring interactions themselves (as stated by Axelrod, 1984), but also in terms of the recurrence of various elements that significantly influence these relations, which include the following (Fig. 1):

- Recurrence of partners (including project consortia) and motivation for partner selection;
- Recurrence of the cooperation theme (e.g. thematic scope) and motivation for its selection;
- Recurrence of the spatial structures of the cooperation (i.e. the locations of the organisations involved in the cooperation) and motivations for participating in the cooperation according to its location.

In the context of the existing body of literature, the stability of cross-border cooperation should, by definition, not be treated as an unambiguously positive or negative phenomenon but, above

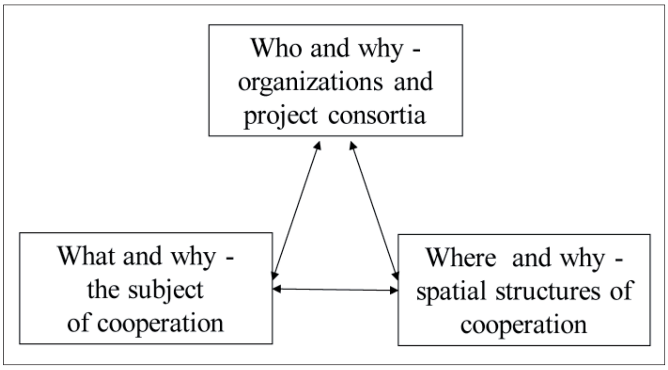

Fig. 1: Concept of the stability of cross-border cooperation
Source: Authors' conceptualisation

all, as a phenomenon that allows for a better understanding of the mechanisms of its functioning. This has been the approach adopted by the authors of this study.

3. Study method and sources

The present analysis of the stability of cross-border cooperation was based on an examination of all the cross-border cooperation programmes approved for implementation under the European Territorial Cooperation (ETC) 2007–2013, the European Neighbourhood and Partnership Instrument (ENPI) 2007–2013, Interreg 2014–2020, and the European Neighbourhood Instrument (ENI) 2014–2020[2]. The study covered a total of 1,577 projects realised between 2007–2013 and 2014–2020 and implemented by more than 4,500 beneficiaries[3], comprising 2,307 organisations.

The analysis focused on Polish border areas running on both sides of the land borders. The maritime border was not included due to the fact that it has distinct characteristics resulting from, among other things, the long distances between the cooperating countries. For the purposes of the stability analysis, the following factors were examined (Fig. 1):

- Recurrence of cooperation partners[4] (who);
- Recurrence of cooperation subject (what);
- Repetition of spatial structures of cooperation (where);
- Motivation for the choice of partners (taking into account their type and location) and the motivation for the choice of thematic scope (why).

The recurrence of cooperation partners was defined on the basis of the recurrence of organisations involved in the cooperation and the types of these organisations (Fig. 1, 'Who'). Overall, this study was based on a statistical analysis of all the organisations involved in cooperation projects, which were divided into three groups: the Polish units, the other EU countries (Germany, Czech Republic, Slovakia, and Lithuania) and the non-EU countries (Ukraine, Belarus, and Russia). The list of organisations was obtained from the databases of the Polish Ministry of Funds and Regional Policy, the technical secretariats of the programmes examined, and the Keep.eu database developed within the INTERACT programme. For the purpose of the analysis, the authors classified organisations into formal and legal categories (Fig. 2).

With regard to the recurrence of the cooperation theme (Fig. 1, 'What'), the study was based on the statistical analysis of all the projects approved for implementation, and the thematic scope of the projects was defined in accordance with the classification of intervention categories for EU funds, which was slightly modified for the purposes of this study. All the projects were attributed to the 2007–2013 categories (OJ L 371, 27.12.2006) by the authors on the basis of the actual (and financially dominant) thematic scope of the projects implemented. This was due to the fact that in the Keep.eu database, projects were declared by partners, which did not always reflect the actual nature of the project. The analyses were carried out in two groups of projects: those implemented in border areas along the internal EU border and those implemented along the external EU border.

Regarding the recurrence of the spatial structures of cooperation (Fig. 1, 'Where'), the study was based on a spatial analysis of the location of all the beneficiaries involved in the cooperation projects. The location was defined on the basis of the headquarters of each organisation. Finally, the analysis of the motivations for the choice of partners and the thematic scope (Fig. 1, 'Why') was conducted using the computer-assisted web interview (CAWI) technique. The study was conducted at the turn of the year 2021/2022. As a result, responses were obtained from 262 organisations, which accounted for 11.4% of all units included in the study. This value included only fully completed surveys, as partially completed surveys were rejected.

4. Results

4.1 Stability of organisations involved in cooperation

According to the model of the stability of cross-border cooperation adopted in the study, the first dimension of cooperation that was examined was the recurrence of organisations involved in cooperating in both adopted programming periods. Out of

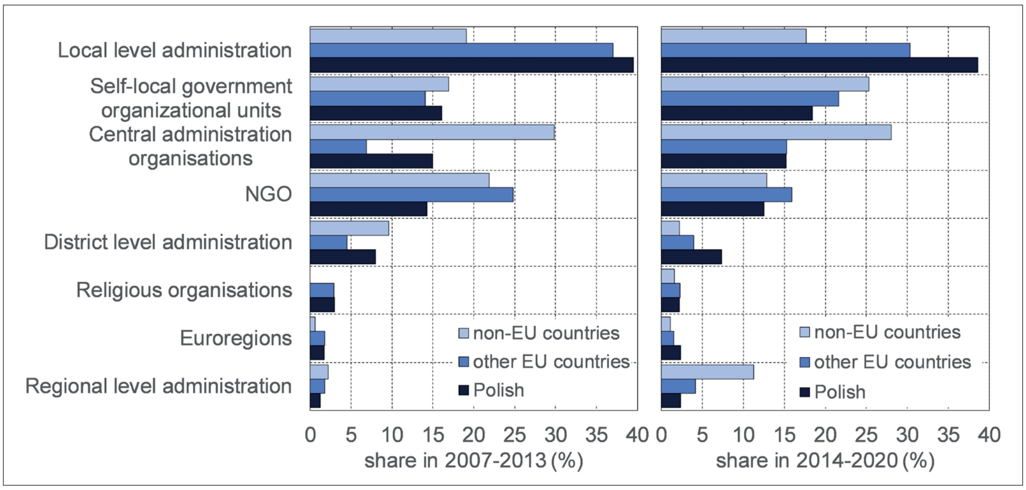

Fig. 2: Formal-legal structure of organisations participating in cross-border cooperation programmes in the Polish borderlands between 2007–2013 and 2014–2020. Source: Authors' survey

[2] The analysis of projects between 2007–2013 covered the following ETC programmes: Mecklenburg–Vorpommern/Brandenburg–Poland, Poland–Brandenburg, Poland–Saxony, Czech Republic–Poland, Poland–Slovak Republic, and Poland–Lithuania. The following ENPI projects were also examined: Poland–Belarus–Ukraine and Lithuania–Poland–Russia. The analysis of projects in 2014–2020, in turn, covered the following ETC programmes: Mecklenburg–Vorpommern/Brandenburg–Poland, Brandenburg–Poland, Poland–Saxony, Czech Republic–Poland, Poland–Slovakia, and Lithuania–Poland. The ENI projects Poland–Belarus–Ukraine and Poland–Russia were also included in the study.

[3] 'Beneficiary' here means a public or private entity responsible for the implementation of an operation (or the implementation of a project; OJ L 347/320, 20/12.2013). In practice, this means that the same organisation can be multiple beneficiaries implementing a variety of projects.

[4] Partners in the text are understood as cooperating organisations.

the 2,307 organisations involved in cooperation projects, only 469 were present in both programming periods (about 19%). This is due to the fact that around 70% of organisations participated in only one cooperation project between 2007–2020. The number of organisations involved in a larger number of projects was relatively low (only 16% of organisations were involved in two projects and 14% in more than two projects). In this context, we can speak of the very low stability of the cross-border organisational system. In terms of country of origin, the level of recurrence of organisations was relatively similar for Polish organisations (22%) and the rest of the EU countries (19%). However, this level was significantly lower in non-EU countries (10%), which could be attributed to the strong influence of the formal-legal barriers typical of the external borders of the EU and the Schengen area.

Another dimension of stability taken into account was the recurrence of the types of organisations in terms of their formal-legal structures. These structures were quite similar in both programming periods (Fig. 2), and their common feature was the clear dominance of local self-government and the relatively small significance of NGOs. In terms of the countries of origin of the organisations in the study, a number of characteristic differences could be identified. In the group of Polish units, local governments were relatively more important, while NGOs played a slightly greater role among foreign organisations from EU member states and central administration units among foreign organisations from non-EU countries. Thus, the observed structure of the organisations partly reflects (1) the roles and competences of particular administrative levels in these countries with regard to the implementation of public policies, and (2) the level of development of civil society and the organisational capacity of this sector.

4.2 Stability of the cooperation theme

The stability of the cooperation theme was examined by analysing the thematic scope of the cooperation projects in both programming periods (Fig. 3). In the thematic structure of the implemented projects, the most important role was played by projects related to tourism, transport, culture, social infrastructure, human capital, and various types of events. The structure of projects implemented at the EU's internal borders was broadly similar in both programming periods. However, there have been significant changes in the EU's external borders. This was due to the evolution of the scope of cooperation, which consisted of a reduction in the share of strictly infrastructural categories (e.g. water supply in the environmental category and community centres in the social infrastructure category). This was accompanied by an increase in the importance of the 'soft' projects (e.g. those in the areas of human capital, social inclusion, and institutional capacity building). The observed changes partly reflect a cooperation policy geared towards improving the cross-border impact (i.e. benefiting the whole cross-border region and being felt on both sides of the border).

Based on the analysis of the recurrence of cooperation theme, we can speak of the relative stability of cross-border cooperation, but this was limited to the internal borders of the EU. At the external borders, significant and meaningful changes in the scope of cooperation could be observed as a result of the constant evolution of its character. It is important to note that at both the internal and external borders, the main thematic categories were similar and included tourism, transport, social infrastructure, and events. In addition, human capital projects played an important role at the EU's external borders. It therefore appears that these main recurring categories formed a permanent core of cross-border cooperation and may continue to shape its character, even in the future.

4.3 Stability of spatial structures

Another dimension considered in this study was the stability of spatial structures. This dimension was examined in relation to the locations of the beneficiaries of cross-border cooperation projects, as presented by localities. This study included beneficiaries because they reflect the activity of individual organisations (i.e. the number of projects they have implemented) and, consequently, the activity of specific regions of the border area. The use of the category of beneficiaries made it possible to show the number of projects carried out by each organisation, as they could be beneficiaries of cross-border cooperation programmes several times.

The analysis of beneficiaries by locality showed that although only one-third of localities recurred in both programming periods, these localities accounted for 70% of all beneficiaries. This was due to the fact that the recurring localities formed key nodes in spatial cooperation structures (Fig. 4), where cross-border activities were carried out by a number of organisations. These were usually urban centres that played an important role in the socioeconomic life of the border area (e.g. due to the location of regional administrations offices or higher education schools). Moreover, some localities stood out from the others, as they were more prone to cooperation due to their specificity (e.g. cities divided by state borders, such as Zgorzelec–Goerlitz, Slubice–Frankfurt, and Gubin–Guben) or those located closest to the border (e.g. Kudowa Zdrój, Náchod, Punsk, and Brest).

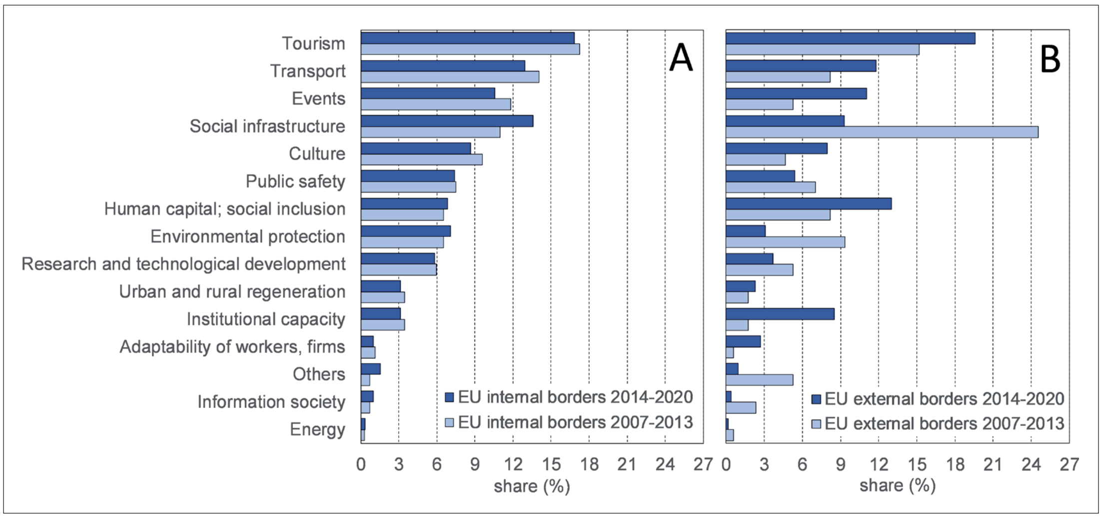

Fig. 3: Cross-border cooperation projects implemented in Polish borderlands between 2007–2013 and 2014–2020 along the internal (A) and external EU borders (B)
Source: Authors' survey

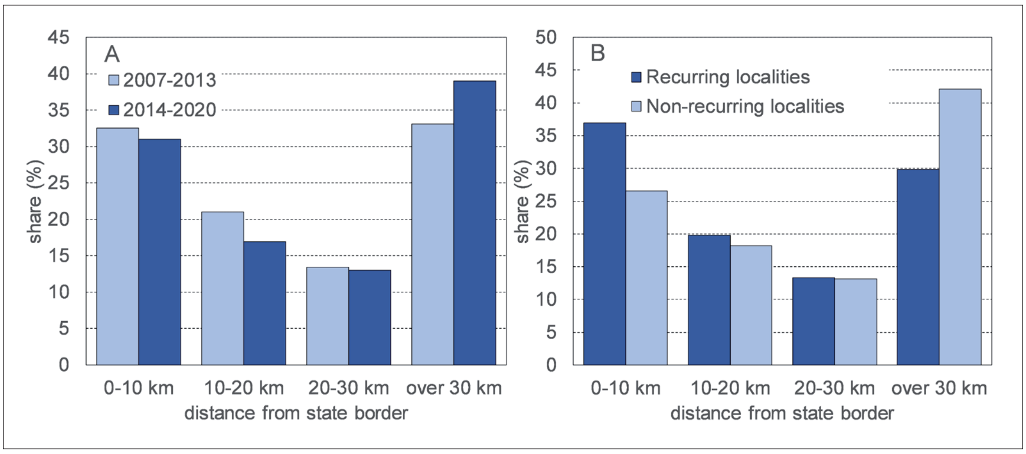

Fig. 4: Structure of localities with beneficiaries of cross-border cooperation programmes (A), as well as recurring and non-recurring localities (B), in 2007–2013 and 2014–2020 in Poland's borderlands by distance from the state border
Source: Authors' survey

The spatial structures of the most important localities (in terms of the number of beneficiaries located within them) were quite similar in both programming periods. At the same time, they formed the backbone of the spatial cooperation structures, which were relatively permanent foundations around which other projects of a less permanent nature were implemented, the latter of which occurred only in one period. Although, as mentioned above, the beneficiaries of cooperation in these localities changed between the two programming periods, this did not have a significant impact on the overall spatial pattern of cooperation.

In the spatial dimension, a decrease in the number of beneficiaries was observed with an increase in the distance from the border (Fig. 4). This phenomenon was studied here in relation to the adopted zones of distance from the border of up to 10 km, 10–20 km, 20–30 km, and over 30 km. More than 30% of the localities were located in the first zone, while 20%, 15%, and 35% were located in the subsequent zones, respectively. Therefore, in this last zone, the factor of proximity to the border did not play a significant role in the establishment of cross-border links. In this zone, the beneficiaries were mostly located in large cities (e.g. Dresden, Lublin, Przemysl, Wroclaw, Uzhhorod, Lviv, Vilnius, or Olomouc), with significant institutional capacities facilitating cooperation even over considerable distances (e.g. numerous public organisations or scientific institutions).

The observed spatial regularities in the distribution of beneficiaries were stable during both programming periods (Fig. 4, Fig. 5). This suggests that the factor of proximity to the border played a significant, stabilising role. This is supported by the observation that in the immediate vicinity of the border, there were definitely more recurrent localities in both periods, and together with an increase in the distance from the border, there was a clear increase in the non-recurrent localities (Fig. 4). At the same time, non-recurring localities predominated in border areas along the external borders of the EU. This may indicate the influence of the nature of the border (in this case, its high degree of formalisation) on the stability of cooperation (Fig. 5).

This study also examined whether the importance of the localities, measured by the number of beneficiaries located within them, was similar in both periods. The correlation between the number of beneficiaries of cross-border cooperation programmes in each locality between 2007–2013 and 2014–2020 was found to be positive and relatively high (+ 0.752). At the same time, in such a case, even the instability of the beneficiaries themselves (e.g. as a result of the exchange of organisations involved in cooperation in subsequent programming periods) did not lead to the instability of the spatial structures of cooperation (which was measured at the level of localities). This demonstrates the relatively stable activity of the most prominent localities in the development of cross-border relations.

Taking into account the results of the research, the spatial structures of cooperation seem to be stable in terms of localities, particularly pronounced in areas in close proximity to the border. And in the case of areas farther away – in regard to the localities most important for cooperation (e.g. major cities).

At the same time, it is worth noting that along the external EU borders, the spatial distribution of the organisations involved in cooperation was much more concentrated, thereby affecting the largest towns in the border area, as well as localities close to border crossings. The proximity of the border itself (apart from the border crossings) did not affect the intensity of cooperation due to its highly formalised nature. In such cases, organisations located in larger urban centres and those with good transport links to organisations in neighbouring countries found it easiest to establish cross-border relations. However, along the EU's internal borders, the spatial structure of the beneficiaries of cooperation was highly dispersed due to the limited formalisation of the state borders.

4.4 Motivation for the choice of partners, scope, and location of cooperation

Another important dimension of the research on partner stability was the analysis of the motivations to establish, continue, or discontinue cooperation, taking into account the issues of the partners themselves, as well as the scope and location of cooperation. This analysis was based on a research survey of organisations, of which 56.9% were Polish organisations, 34.7% were organisations from other EU countries (Germany, Czech Republic, Slovakia, and Lithuania), and 8.4% were organisations from non-EU countries (Ukraine, Belarus, and Russia).

According to the respondents, among the most important factors for establishing cooperation in all types of border areas, the community of objectives played the most dominant role (selected in over 70% of responses; Fig. 6). Spatial accessibility to the partner (around 50%) was also very important, allowing for more frequent direct interactions. This factor corresponds to Axelrod's (1984) observation that an important condition for the establishment and stability of mutual relationships between partners is their frequency (recurrence). It should be noted that, contrary to the results of this study, in the case of cross-border cooperation, the frequency of relationships alone may not have been sufficient to establish cooperation unless accompanied by other factors, such as the shared objectives mentioned above. Expected benefits (material and non-material) also played an

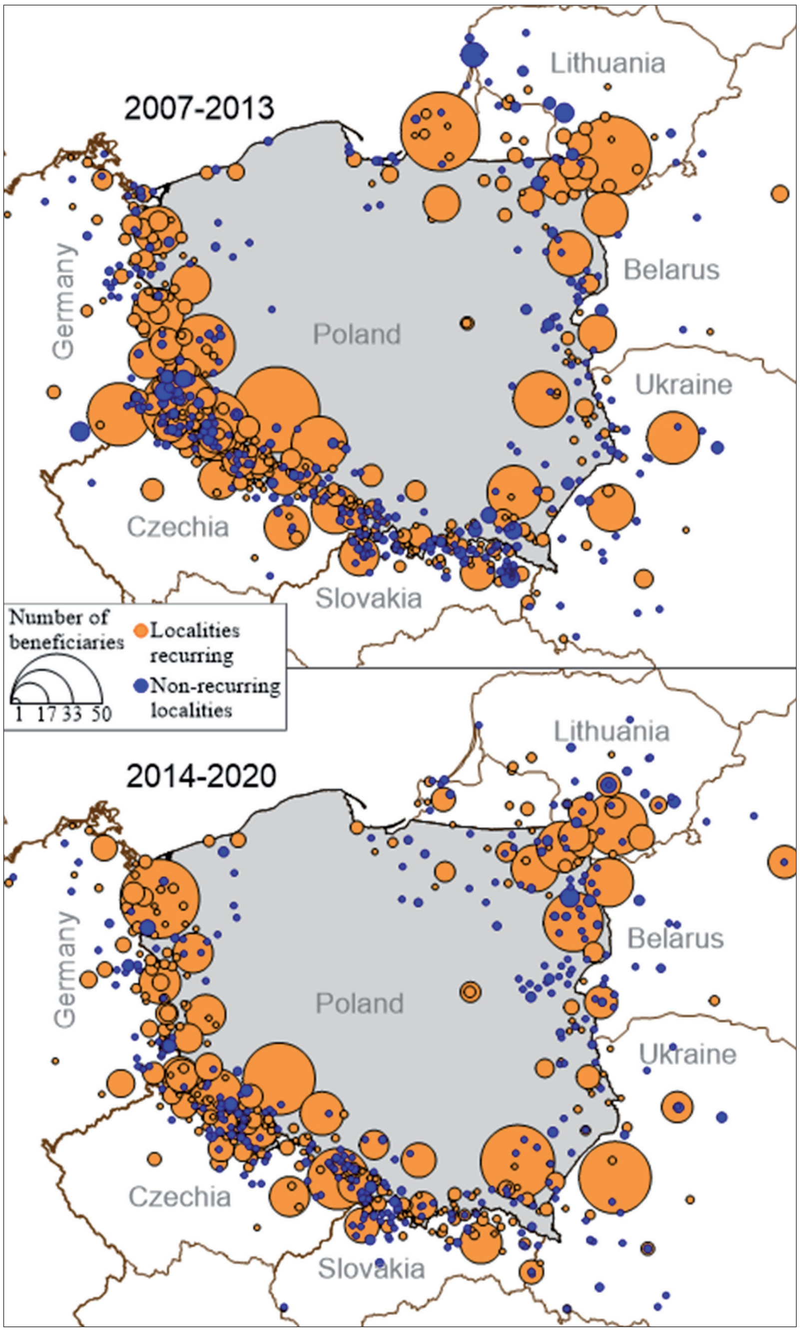

Fig. 5: Localities by the number of beneficiaries of cross-border cooperation projects implemented in Polish borderlands, both recurring and non-recurring, between 2007–2013 and 2014–2020
Source: Authors' elaboration

important role, which were most often organisational benefits and less often community benefits (e.g. local community integration). Personal contacts were also highly significant.

In light of the results obtained, the establishment of cross-border relations with a particular partner for the purpose of implementing a joint project was most often the result of the complex interaction of a number of premises, rather than the impact of a single factor.

The average number of stated premises was five for Polish organisations and about six for organisations from neighbouring states. This shows that the establishment of cross-border cooperation should be understood as a multifaceted and internally complex process, which, by definition, is relatively difficult to freely shape within a cooperation policy. At the same time, although the process reflects the very different objectives of individual organisations, in most cases, they are not mutually exclusive, but can be mutually supportive in a synergistic way. In this context, the main challenge seemed to be combining organisational benefits with those of the community at large.

From the point of view of the stability of cross-border relations, some of the premises identified seemed to favour stability (e.g. geographical stability or previous cooperation), while others did not (e.g. expected benefits for the organisation). Thus, the achievement of stable relations seems to depend to a large extent on the nature of the common objectives underpinning this cooperation – that is, to what extent they are long-term, and to what extent they are temporary (or even accidental).

Among the factors that influenced the partners of projects implemented between 2007–2013 to continue this cooperation in the following programming period (2014–2020), positive experiences from the previous period played a decisive role (selected

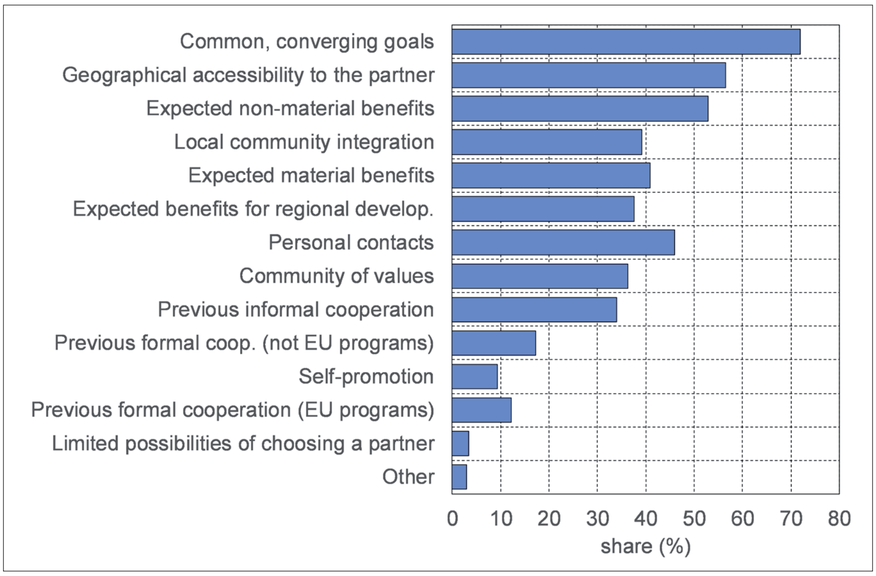

Fig. 6: Premises of establishing cooperation according to organisations participating in cross-border cooperation projects implemented in the Polish borderlands between 2007–2013 and 2014–2020
Source: Authors' survey

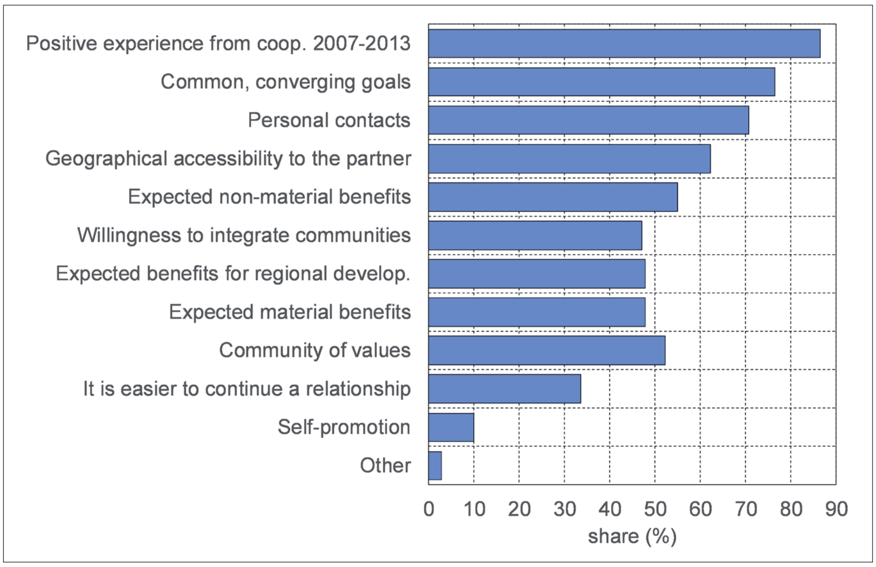

Fig. 7: Premises of continuation of cooperation established between 2007–2013 and continued between 2014–2020, according to organisations participating in cross-border cooperation projects implemented in the Polish borderlands
Source: Authors' survey

in over 86% of the responses; Fig. 7). Therefore, the more successful the projects were from the point of view of all the participating organisations, the greater the likelihood of further joint activities in the future. Notably, a group of eight prominent factors for establishing cooperation (Fig. 6) also played a key role in their continuation (Fig. 7). At the same time, the combined importance of these factors was, in all cases, even greater for the continuation of cooperation, with an analogous hierarchy of importance to the establishment of cooperation. This confirms the special role of the identified premises in shaping cooperation at different stages. It also suggests that the formulation of cooperation policies aimed at strengthening the group of premises serves both to establish and maintain cross-border relations. The relative similarity of the premises for establishing and maintaining cooperation may also suggest that the barriers (constraints) to cooperation are the most important premises in determining whether established relationships will continue in the future.

In this context, particular attention should be paid to the factor of personal contact, which was much more important for maintaining cooperation than for establishing it (by 19 percentage points). This probably reflects the high importance of mutual trust and the intensity of informal relations. For this reason, the implementation of joint projects should aim to strengthen informal interpersonal contacts, as they significantly improve the conditions for further continuation of cooperation. At the same time, however, the fact that the cooperation of organisations is based on the relationships of individual persons only poses a serious threat to their stability in situations where these persons disappear (e.g. after termination of employment). Thus, the creation of a network of personal relationships that is numerous (on the scale of a particular organisation) and resistant to random events and the natural phenomenon of staff turnover could affect the stability of cross-border relations.

Approximately one-third of respondents highlighted the importance of being able to continue existing relationships rather than starting new ones from scratch. This factor, therefore, favours the stability of cross-border relationships. However, it could also be linked to organisational inertia. It is, therefore, difficult to say unequivocally whether this factor has a positive or negative impact on cross-border cooperation in the long term.

With regard to the premises identified by the respondents as being responsible for the lack of continuation of cooperation, the low number of premises is noticeable (at around two). To establish or continue with cooperation, many factors had to occur simultaneously (i.e. more than five). However, only a few factors were needed for cooperation to cease. In other words, the premises identified by the respondents as conditioning the lack of cooperation were most often those that definitely excluded further activity. This fact seems to clearly explain the low repeatability of the organisations involved in cooperation.

Non-continuity of cooperation was found to be mainly related to financial issues, and mostly an entity's own insufficient resources to finance or co-finance joint ventures (reflected in over 24% of responses; Fig. 8). A group of six factors with similar shares also played a significant role (12–16%). This group included formal issues that were mostly related to restrictions or changes in the thematic scope of support, the eligibility of expenditure, the functioning of project consortia, or the fact of not receiving support from EU funds. Premises in this group include those related to a change in the priorities of the cooperating organisations, differences between their objectives and working methods, and limitations in the scope of human resources.

Among the factors identified, language, which is often described in the academic literature as an important barrier to cross-border cooperation (Medeiros, 2018), was relatively insignificant. This is due to the fact that the study examined organisations involved in cooperation, which would have had to overcome this barrier before.

5. Conclusions

This research has shown that, in general, while there is relative stability in the types of partners, thematic scopes, and spatial dimensions of cross-border cooperation, there is instability in organisational terms. In addition, this study has revealed that the establishment and subsequent maintenance of cross-border relationships are the result of a complex process in which several factors simultaneously co-exist. What seems to be significant is that the set of conditions that are important for establishing and maintaining cooperation is relatively similar. At the same time, very few premises (one or two) seem to be required for cooperation with a given partner to break down (e.g. a lack of financial sources). These results, therefore, illustrate the relative fragility of cross-border relations and show that cross-border cooperation, in its formal dimension, is characterised by an inherent lack of stability, with stability here understood as the repeatability of cooperation partners. This is in line with previous findings indicating a low level of organisational stability, as well as partnership stability, in cross-border cooperation projects financed by EU funds. At the same time, it appears that the low level of repeatability of cross-border relationships can be partly explained by low exit barriers, which are a typical feature of cross-border cooperation projects. Low exit barriers could be the result of a low sense of identity and community in border regions (Gaudeul et al., 2017). Under such conditions, the strength of social control (which increases barriers to exit) is usually low (Jafroudi, 2018).

On the basis of the above conclusions, it can be stated that the cross-border cooperation policy, regardless of the level at which it is formulated, should support all the factors that influence its establishment and continuation (not just certain ones) in a complex way. Moreover, it should address all the main barriers to such cooperation. Additionally, it must also take into account the observed instability of cooperation between organisations. For this reason, the most important cooperation nodes in specific border regions are crucial, as they have the highest potential for fostering stability (Dołzbłasz & Raczyk, 2021). In this context, a broader discussion should be held on the most desirable model of development for cross-border cooperation – whether it be based on supporting the most stable cooperation nodes, or perhaps focus on incorporating the highest possible number of new organisations, which would lead to instability of the organisational set-up involved in cross-border relations. Perhaps the most beneficial solution would be to adopt a hybrid model, combining, on the one hand, the existence of a small number of main cooperation nodes that have been stable over time, and, on the other hand, a large group of organisations involved in cross-border projects on a more sporadic basis.

The research conducted here shows that cross-border cooperation in Polish border areas can be described as partially stable in terms of the subject of cooperation, which is limited only to the thematic categories selected as the most popular (e.g. tourism, transport, events, and culture). It is important to note that among the group of reasons for starting and continuing cooperation, those focused on achieving the organisation's own objectives, rather than those of the community as a whole, dominated. This situation can be

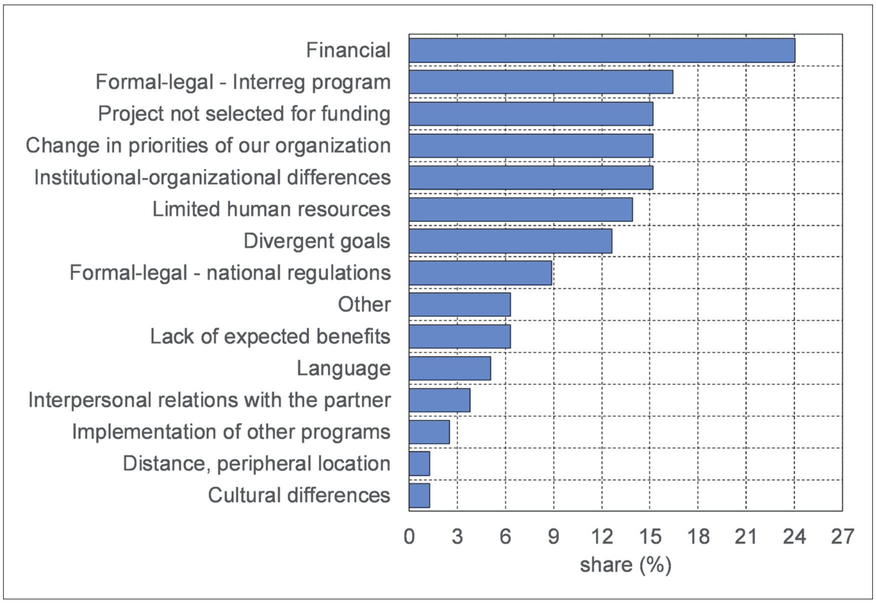

Fig. 8: Premises of discontinuation of cooperation in the next programming period (2014–2020) according to organisations participating in cross-border cooperation projects implemented in Polish borderlands between 2007–2013
Source: Authors' survey

explained by the low sense of community and low barriers to exit typical of border regions (Gaudeul et al., 2017).

From a spatial point of view, an overall stability of the general distribution of beneficiaries was observed, including the repeatability of localities. This phenomenon occurred despite the instability of the organisations themselves, which were the beneficiaries of the cooperation projects. The stability of the spatial distribution was determined by the distance from the border and its nature (i.e. it differed at the internal and external EU borders). In this context, it seems justified to carry out further research on the question of which dimension of stability is the most important for the shaping of cross-border cooperation: the stability of the subject of cooperation, its spatial structures, or the partners. Furthermore, it is critical to examine the extent to which the importance of these dimensions differs across border areas. Studies of border regions generally do not offer a single, universal pattern for the development of cross-border cooperation. This is partly due to the fact that cooperation is shaped differently in various border regions, as the entities involved in this cooperation are set in diverse conditions that are hardly comparable (Leibenath & Knippschild, 2005). Irrespective of whether the stability of cooperation in border regions is universal or perhaps more specific (unique) in nature, it appears to be worth investigating.

The results of this study are in line with the conceptualisation presented by Axelrod (1984), who pointed to the importance of the frequency and recurrence (as well as the inevitability) of mutual interactions as a prerequisite of shaping stable cooperation. Recurrence in border areas is most likely to occur in the immediate vicinity of the border and decreases with the distance from it. The influence of spatial proximity on the shaping of relationships has also been underlined in other studies (e.g. Boehmer & Peńa, 2012). Moreover, the repetitiveness of mutual interactions can be conditioned by the institutional potential of individual localities and their position in the functional–spatial connections in each border area. This explains the role of large towns, even those farther away from the border, in generating cooperation. Boehmer and Peńa (2012) are among those who have pointed out the importance of major urban centres in intensifying cross-border links. In terms of the stability of the cooperation theme, it was associated with the most popular categories and accessible to a considerable number of different organisations.

It is worth noting that, as shown by Van Der Zwet and Vironen (2013, p. 247), cooperation programmes constitute a continuous learning process, and continuity, stability, and maturity are key factors of territorial integration. At the same time, as noted by Van Houtum (1998), the stability of cooperation can lead to its 'decay' and the so-called 'lock-in' mechanism, which reduces the elasticity and creativity of entities involved in cooperation. Thus, in the implementation of cross-border cooperation, it may be useful to strike a balance between the needs for both elasticity and stability (Biot, 2013).

6. Limitations of the study

It should be taken into account that the analysis was based on a study of cross-border cooperation projects co-financed with EU funds. These projects represent one (albeit the most important) of many different forms of cooperation. Hence, the study does not take into account, among others, company cooperation, informal relations between people, European Grouping of Territorial Cooperation, and the conclusions of the study therefore apply only to cross-border projects. The stability of cooperation, for example, of companies or people, may be driven by different rules.

A major problem is the lack of a single definition of the concept of stability, which makes it difficult to conceptualise it in relation to cooperation, including cross-border cooperation in particular.

Although all cooperation projects in the analysed borderlands were included in the study, the conclusions drawn from the survey were based on 262 complete responses (from 11.4% of all organisations). The surveyed population may not be fully representative of all organisations, e.g. by the fact that there may be an overrepresentation of entities actively working in the field of cooperation.

In the study, the spatial dimension of cooperation was examined in relation to the location of organisations implementing joint projects. The location of project activities was not taken into account due to the lack of available data in this aspect.

Due to the peculiarities of border areas (Anderson & O'Dowd, 1999; Paasi & Ferdoush, 2023), the observed regularities may be somewhat different in the borderlands of other countries and change over time. At the same time, it seems appropriate to carry out further research into the factors that lead to the establishment of cross-border relationships (prerequisites for cooperation). It is also crucial to investigate the premises related to the stability of organisations and their cross-border partnerships, particularly those related to the issue of trust and low barriers to exit that pose a threat to group cohesion (Gaudeul et al., 2017) or cultural differences.

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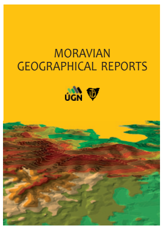

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Tracing the fate of hay meadows with haylofts in Slovakia: A geographical perspective

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Abstract

The paper focuses on the historical distribution of haylofts in Slovakia, geographical conditions related to hay meadows with haylofts, and land cover changes of former hayloft localities. Moreover, the current state of preserved haylofts and the land use of their surrounding area were documented at a regional scale, during the field research. A map of the historical occurrence of haylofts was digitised based on the Czechoslovakian military topographic maps from 1952–1957 (1:25,000). Altogether, 9,742 haylofts were recorded. The haylofts were usually built in mountain and sub-mountain areas on places with low soil quality, mostly at higher elevations, on moderate or moderately steep slopes and in more distant and isolated areas. About half of former hayloft meadows now exist as meadows or pastures with different intensity of grassland management. Forest or shrubs already cover the other 38% of the sites. To a lesser extent, the areas have been converted into arable land or recreational areas. Only a few haylofts have survived to this day; for example, in Upper Liptov Region, it is only 1% of their former abundance in this area (48 haylofts). Apart from a few positive cases where they have been restored or preserved, those that have survived continue to decay.

Key words: *Land abandonment, land cover, grasslands, agricultural history, traditional management*

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1. Introduction

Hay meadows are an important cultural, ecological, and agricultural feature of the landscape, which has been seriously threatened by changes in agricultural practices over the last century (Riley, 2006). Historically, hay meadows were managed with low intensity, that means farming before the spread of modern farming methods connected to chemical fertilisation, drainage, reseeding, and mechanisation often involving a combination of haymaking and pasturing (Janišová et al., 2023) and were characterised by highly diverse vegetation (Sullivan et al., 2018). Several studies around Europe indicated the threats of traditional hay meadows abandonment connected to loss of biological diversity (Norderhaug et al., 2000; Myklestad & Sætersdal, 2003; Marini et al., 2007; Csergő et al., 2013) and cultural heritage associated with hay-making structures (Kruse et al., 2023). Despite its significant decrease since the mid-twentieth century, the fragments of hay meadows can still be found in the landscape. Together with traditional hay making structures, e.g. haylofts and hay sheds, hayloft meadows represent a cultural legacy of traditional landscape management and contribute to biodiversity preservation (Špulerová et al., 2019; Kruse et al., 2023).

In Slovakia, several regions with preserved traditional grassland management were recently documented; however, these systems are preserved without original haymaking storage in haylofts (Janišová et al., 2021) and the haylofts themselves can be found only sporadically. Despite the frequent abundance of haylofts in mountain and sub-mountain areas in the past, there is no comprehensive study on their overall distribution and geographical conditions of their development, nor is the knowledge about the current state of their preservation. The aim of the paper is to fill the gap in this area with focus on the following: 1) historical distribution of haylofts in Slovakia; 2) geographical conditions related to hayloft distribution; 3) changes in land cover of former hayloft meadows; and 4) current state of preserved haylofts and the land use of their surrounding area, and thus to contribute to their knowledge in context of promoting and protecting this biocultural heritage.

2. Theoretical background

Majority of grasslands in Central Europe were developed by human activity, which replaced original forests and open woodland vegetation (Hejcman et al., 2013). Several traditional agricultural systems have been developed in meadow-pastoral landscape, which represent a legacy of traditional management of the European landscape (Burton & Riley, 2018). They include silvopastoral systems, generally referring to ecosystems with sparse trees in open grasslands (Eichhorn et al., 2006; Hartel et al., 2015) that represent one of the oldest land-use types across Europe (Stevenson & Harrison, 1992; Luick, 2008), orchard meadows typical for

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temperate Europe that are connected to different ecosystem services (Forejt & Syrbe, 2019), and to traditional ecological knowledge (Hammel & Arnold, 2012; Žarnovičan et al., 2017; Hutárová et al., 2021; Philipp & Zander, 2023), or hay meadows, that have spread mainly due to the increased cattle breeding and together with significant presence of woody vegetation and typical haylofts, they created the traditional landscape scenery and local colour of mountain and sub-mountain areas (Podolák, 1982).

The European traditional land-use systems have mainly persisted in upland and remote areas where physical constraints have prevented a modernisation of agriculture (Plieninger et al., 2006; Solymosi, 2011; Lieskovský et al., 2014). Previous research has demonstrated the importance of biophysical characteristics such as slope gradient, altitude, or soil quality as drivers of changes when studying traditional landscapes (Rey Benayas et al., 2007; Monteiro et al., 2011; Müller et al., 2013; Druga & Falťan, 2014; Cvitanović et al., 2017).

Hay meadows were preserved in Slovakia until the beginning of agricultural collectivisation, which took place during the communist era (Bezák & Mitchley, 2014; Janišová et al., 2023). The collectivisation process included confiscation of private farmers' property, the establishment of cooperatives and the subsequent land consolidation, and the gradual formation of large-scale agricultural landscapes (Jepsen et al., 2015; Izakovičová et al., 2022). Intensification techniques such as drainage, sowing (after ploughing) or reseeding (without ploughing) of grass and clover cultivars, and intensive fertilisation have completely disrupted the traditional way of farming (Halada et al., 2008), that included clearing the meadows in spring (removing branches and stones), manual mowing once a year, typically in early July, traditional hay-making structures for drying and storage of hay, grazing by livestock in late summer and autumn, and raking in spring and autumn that also provided fertilisation for the meadows (Podolák, 1961). As a consequence of the intensification, there has been a significant impact on the species composition, fostering the development of intensive, species-poor stands (Halada et al., 2008), along with the removal of non-forest woody vegetation and haylofts.

The haylofts are an indelible part of the hay meadow cultural landscape and reflect the former traditional use of mountainous areas (Kušar & Komac, 2019). They are one of the last remaining signs of rural architecture (Palanti et al., 2014). During the winter, haylofts served as storage spaces for hay, which was typically transported to villages using sleighs, usually in the months of January or February. (Podolák, 1962). The system of hay storage was used not only because of the lack of space in the village, but also for safety reasons due to the frequent fires that affected villages with wooden architecture (Podolák, 1982). Construction of haylofts reflected the natural environment in which they were located (Kušar & Komac, 2019). For example, in Italy and Slovenia they were made mainly of wood (Kruse et al., 2023), in France of stone, or wood (Robert, 1942), and comparable stone-built buildings for hay storage exist also in the Pennines in England (Špulerová et al., 2019). In Slovakia, there were only wooden log buildings. They were approximately 4 × 4 metres in size, with roofs covered by shingles (see Fig. 1). Haylofts were without windows and often without doors (Podolák, 1982). The hay was placed in them through a hole in the gable or in the wall of the log cabin. The haylofts were widely distributed in mountain and sub mountain regions of Slovakia and they were built on the lowest mountain meadows, usually on moderate slopes and above the upper edge of the forest (Podolák, 1962).

Although hayloft meadows were widely spread in the Carpathian Mountains and in the Alps (Kruse et al., 2023), the studies targeting haylofts are quite rare. They were devoted to distribution and types of haylofts in France (Robert, 1942), ways of their construction in England (Roberts, 2011), or the classification of the levels of decay in Slovenia (Kušar & Komac, 2019). In Slovakia, ethnographers studied the haylofts only marginally in relation with the local traditional ways of meadows management and hay storage (Podolák, 1961; Podolák, 1962; Podolák, 1982).

3. Methods

The research was carried out at two levels. At the national level, historical distribution of haylofts, evaluation of geographical factors and land cover change was performed. At the regional level, the region with the highest historical occurrence of haylofts was selected to identify the present state and use of preserved haylofts and the land use of the surrounding landscape.

3.1 Study area

Slovakia is located in the Central European region. The georelief is characterised by the mountain arc of the Western Carpathians with a typical alternation of diverse rocks (flysch, crystalline, carbonate and volcanic rocks). The relief culminates in the alpine parts of the High and Low Tatras in northern Slovakia with the highest peak Gerlachovský štít, reaching 2,655 metres a.s.l. The lowlands are located in the south and southeast of Slovakia, with

Fig. 1: The haylofts in historical photographs in 1950s: Meadows with solitaires of trees and haylofts (left) and haylofts in the cadastral area of Východná (right)
Source: The archive of Východná municipality (2002)

the lowest point at Dolný Zemplín near the Bodrog River, which reaches 94 metres a.s.l. The population density is 111.2 per km^2, and the total area is 49,034 km^2. According to the Statistical Office of the Slovak Republic (2021), lowlands (up to 300 metres a.s.l.) occupy 41% of the territory, low highlands (301–750 metres a.s.l.) occupy 45% of the territory, and areas over 751 metres up to 2,655 metres occupy 14% of Slovakia. For generations, the Slovak economy has been heavily dependent on agriculture. The lowlands are suitable for cultivating crops such as wheat, barley, corn, or vegetables. The hilly and mountainous regions are more suitable for animal husbandry, such as cattle and sheep breeding.

Regional study was carried out in the Upper Liptov Region, situated in the northern part of Slovakia (Fig. 6), between the Low Tatras Mts. in the south and the High Tatras Mts. in the north. The majority of the region belongs to a moderately cold and very humid climatic area, with soils dominated by pseudogleys, cambisols and rendzinas (Atlas of the Landscape of the Slovak Republic, 2002). The area covers 805 km^2. The area was settled from the 13^{th} century, and was influenced by three colonisation waves – German, Wallachian and partially highlander colonisation (the last two were shepherds). Due to the harsh climatic conditions, the animal husbandry oriented towards sheep and cattle breeding prevailed. Until 1948, the region consisted of 18 municipalities.

3.2 Mapping the historical distribution of haylofts

Identification of the historical distribution of haylofts in Slovakia was based on Czechoslovak topographic military maps (1:25,000) from 1952–1957. The maps were produced by the Military Topographical Institute in Banská Bystrica using a photogrammetric foundation. Online version of the map set is provided by the Ministry of the Environment of the Slovak Republic, freely available at the National Geoportal (https://geoportal.gov.sk/maps/historical-maps/). Maps show the situation before, or at the very beginning of the establishment of cooperative farms linked with agricultural intensification and collectivisation. The identification of hayloft meadows and pastures on the historical maps is documented in Figure 2. Haylofts were digitised to point GIS layer. The data were processed using the ArcMap 10.3 software (ESRI, 2016) that was used for all GIS procedures applied in this study.

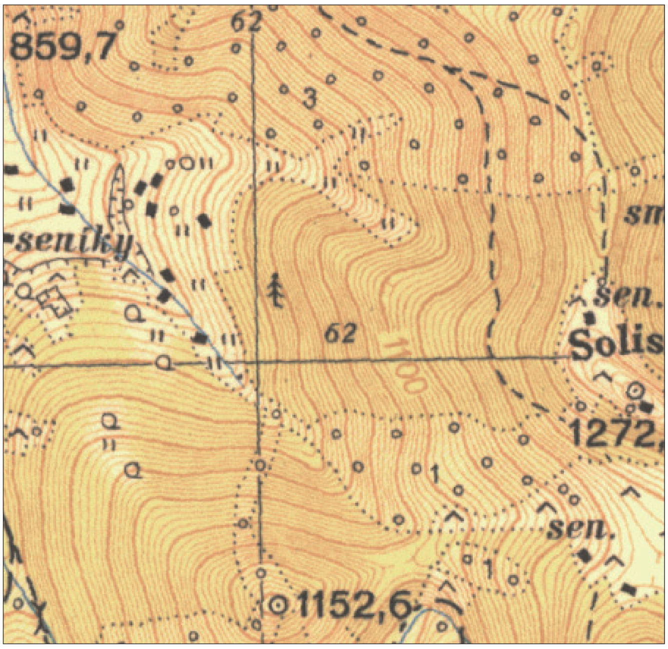

Fig. 2: Military topographic maps from 1950s
Source: National Geoportal
Legend: ■ *sen./seníky – hayloft/haylofts, " – meadow, ^ – pasture*

3.3 Analyses of geographical factors

We identified the environmental conditions of hayloft meadows based on literature, expert knowledge of the area and the data availability. We performed a correlation analysis (see Appendix 1) and chose the most representative variable from the strongly correlated ones. We chose altitude and slope as basic relief characteristics explaining the haylofts distribution. The topographic data were obtained from a digital elevation model (DEM) with resolution 30 m that was derived from contour maps at the scale of 1:10,000.

Soil fertility was obtained from the national database of soils provided by the National Agricultural and Food Centre in Bratislava. Fertility is expressed as soil production potential derived from soil type, slope steepness, aspect, skeletal content and depth, grain size distribution, and climate factor (Džatko, 2002). The soil production potential is expressed on a relative scale of zero (the least productive soils) to 100 (the most fertile soils).

From the distance factors, we analysed accessibility and isolation. Accessibility was evaluated as walking distance from the nearest settlement in minutes. The analysis included the effect of topography and different land cover types that could slow walking speed (meadows, cropland, forest), could have a barrier effect (buildings, rivers), or could facilitate walking (paved roads, paths, bridges, etc.) (Druga & Minár, 2023; Lieskovský et al., 2017; Rusinko & Druga, 2022). As a source of land-cover data, we used the Corine Land Cover from 1990 (European Environmental Agency & Copernicus Land Monitoring Service, 2019) as the oldest available national-wide land-cover data source, which reflects the closest available source to the years of mapping haylofts. The effect of different land cover classes on walking speed were derived from empirical experiences and from published literature (Soule & Goldman, 1972; Mezníková, 2011; Lieskovský et al., 2014).

Similarly, the isolation was evaluated as the distance by car to the regional centre in minutes. We employed the present-day road network map, excluding newly constructed highways since the time of collectivisation. We did not have the information about average car speed on the roads; therefore, we employed maximum car speeds limits: 120 $km.h^{-1}$ for established highways and 90 $km.h^{-1}$ for roads. Additionally, we incorporated pedestrian distances from roads to the hayloft areas inaccessible by car. The VARCOST module from the IDRISI software was used for the analysis.

Microclimatic variables were represented by solar radiation. Solar radiation expresses the average amount of solar energy received from the sun per year. It was calculated with the Area Solar Radiation tool included in ArcGIS Spatial Analyst toolbox from a digital elevation model with resolution 10 metres. We did not consider classical climate variables as average temperature or rainfall, because they are strongly correlated to the altitude.

To analyse the role of geographical factors related to the haylofts' occurrence, we compared the distribution of haylofts with the historical distribution of grasslands. The information on the historical grassland distribution was taken from the map of historical land cover of the Carpathian region (Lieskovský et al., 2018). The land cover was mapped in a 2 × 2 km point square grid from the Czechoslovak topographic military maps at the scale of 1:25,000 from 1952–1957. Four classes represented the grasslands: wet meadows, dry meadows, wet pastures, dry pastures. For our analyses, we selected dry meadows and dry pastures, because the haylofts were not situated on wetlands. Due to the high spatial autocorrelation of the hayloft data, we were not able to perform a statistical test of significance of the differences.

3.4 Analysis of historical land cover of hayloft localities and changes of land cover (1950s–2018)

We used the same maps for historical land cover of hayloft localities as we did for the identification of haylofts. Meadows and pastures, distinguished on the maps as two categories (Fig. 2), were merged into one category as grasslands for further studying the land cover changes. To identify current land cover, we used the CORINE land cover map (European Environmental Agency & Copernicus Land Monitoring Service, 2019), but some categories were slightly modified (Tab. 1). In order to determine land cover classes accurately, their occurrence was manually compared with aerial photographs from 2018 to minimise the error rate (this mainly concerned small grasslands or their peripheral parts that were included in the forest area under the CLC). We distinguished following land cover categories given in Table 1.

To document the current state and condition of preserved haylofts and the land use in their surrounding area, a field survey was performed in 2022–2023 in the Upper Liptov Region. The area was selected on the basis of the highest number of identified haylofts among the regions of Slovakia (Fig. 1). We identified the occurrence of haylofts based on our previous research knowledge and the aerial photographs from 2020. All identified haylofts were subsequently verified in the field, photo documented, and classified according to modified classification of Kušar and Komac (2019) to three categories: (1) without visible damage; (2) partly, or entirely damaged roof, wall timbers without damage; (3) damaged wall timbers, or just some remnants of logs, or traces visible, but still possible to identify the hayloft´s layout.

4. Results

4.1 Historical distribution of haylofts

In the whole territory of Slovakia, we identified 9,742 haylofts, which were localised in the cadastres of 161 municipalities (5.57% of the total number of municipalities in Slovakia) and 26 districts. Hayloft meadows were unevenly distributed across Slovakia. We identified three main spatial clusters of hayloft distribution (see Fig. 3):

1. Partially the counties of Liptovský Mikuláš and Poprad (historically the Upper Liptov Region) – 4,537 haylofts (46.57% of all identified haylofts);
2. Partially Ružomberok and Martin districts (partially the former Lower Liptov Region and Turiec region), with 1,820 haylofts (18.68% of all identified haylofts);
3. Partly the counties of Banská Bystrica and Zvolen (historically partially Zvolen County) had 1,204 haylofts (12.36% of all identified haylofts).

4.2 Geographical conditions related to haylofts distribution

The haylofts were localised at higher elevations peaking at altitudes of 700–900 m a.s.l. From this point onwards, their number gradually decreased with increasing altitude. The mean altitude of haylofts was 819 m a.s.l. (standard deviation 180 m), which differed significantly from the average value of altitude of grasslands (522 m a.s.l., and standard deviation 320 m). Most of the haylofts were located on moderate or moderately steep slopes, with

Land cover type	Description
Forest	Broadleaf, coniferous and mixed forests
Shrub communities	Succession stages with dominance of shrub communities, riparian shrubs
Water bodies	Water dams and fishponds
Grasslands	Meadows, pastures and natural grasslands above the treeline
Land principally occupied by agriculture	Mosaics of small patches of arable land and grasslands
Arable land	All arable lands except of small patches of arable land in mosaics with grasslands
Discontinuous urban fabric	Residential areas and residential facilities, including individual houses, roads within residential areas, home gardens
Industrial units and roads	Mining areas, industrial units, roads, motorways and motorway rest areas
Sport and leisure facilities	Sports fields, recreational areas, or individual cottages mapped within 30 m radius from the historical occurrence of haylofts

Tab. 1: Identification and classification of preserved haylofts at regional level
Source: Authors' elaboration

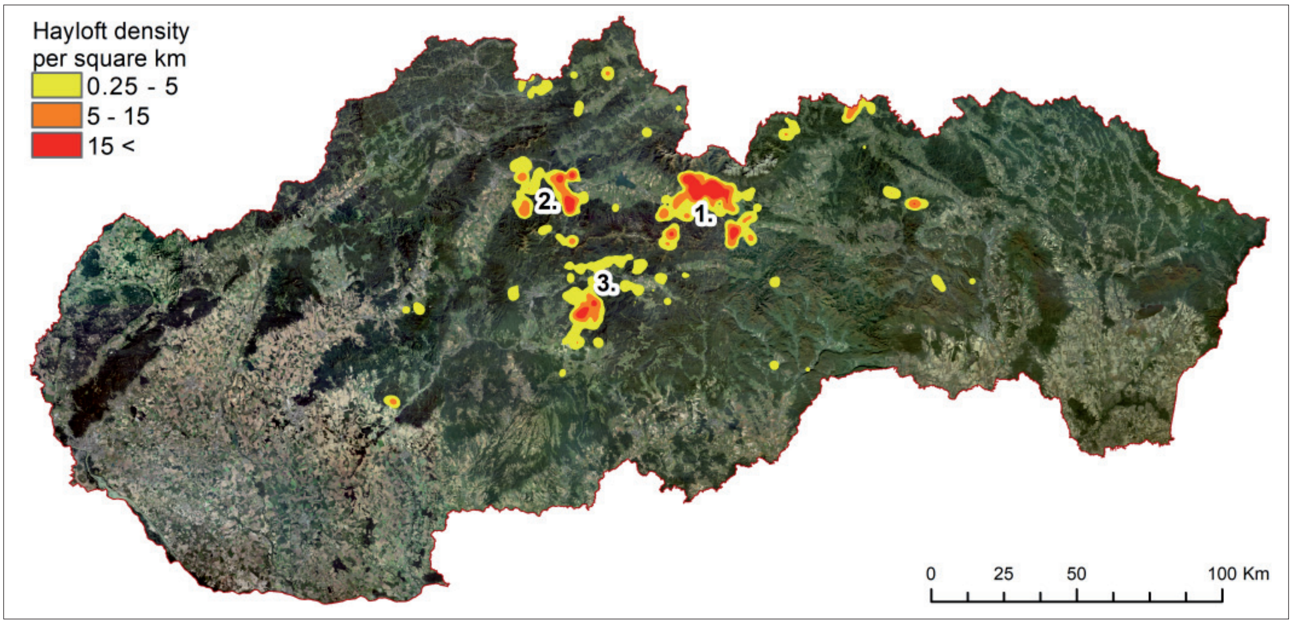

Fig. 3: Hayloft density in 1950s
Source: Authors' elaboration

maximum reaching 37 degrees. Although haylofts were favoured on locations with slightly higher slopes, the average slope values of hayloft localities (10.1 degrees, standard deviation 6.7) and grasslands (9.7 degrees, standard deviation 7.8) were similar.

The haylofts were built in locations with less fertile soils ranging mostly from 20 to 30 of soil quality (on the scale of zero with the least productive soils, to 100 with the most fertile soils), an average value of 25 (standard deviation 11.5), in contrast to grasslands with average soil quality of 37 (standard deviation 21.1). The "distance to village" indicator shows that haylofts were more remote from the nearest villages – 67 min on average (standard deviation 35.3) compared to grasslands (mean distance of 47 min, standard deviation 42.4). The attribute of "distance from regional centres" also documents that areas with haylofts were more isolated. Average distance from regional capital city by car was 62.1 min (standard deviation 29.2) to haylofts and 59.3 min (standard deviation 47.2) to meadows. The differences in median value are even more noticeable (Fig. 4). The haylofts were built in areas with slightly higher solar radiation. Average solar radiation was 1,199,792 $Wh.m^{-2}$ (standard deviation 117,772) for haylofts and 1,181,361 $Wh.m^{-2}$ (standard deviation 100,666) for meadows.

4.3 Changes in land cover of hayloft meadows

In the past, almost all haylofts were located on meadows or pastures, only a few of them were located at the edge of the forest or even on edges of fields (0.5% of all recorded haylofts). More than

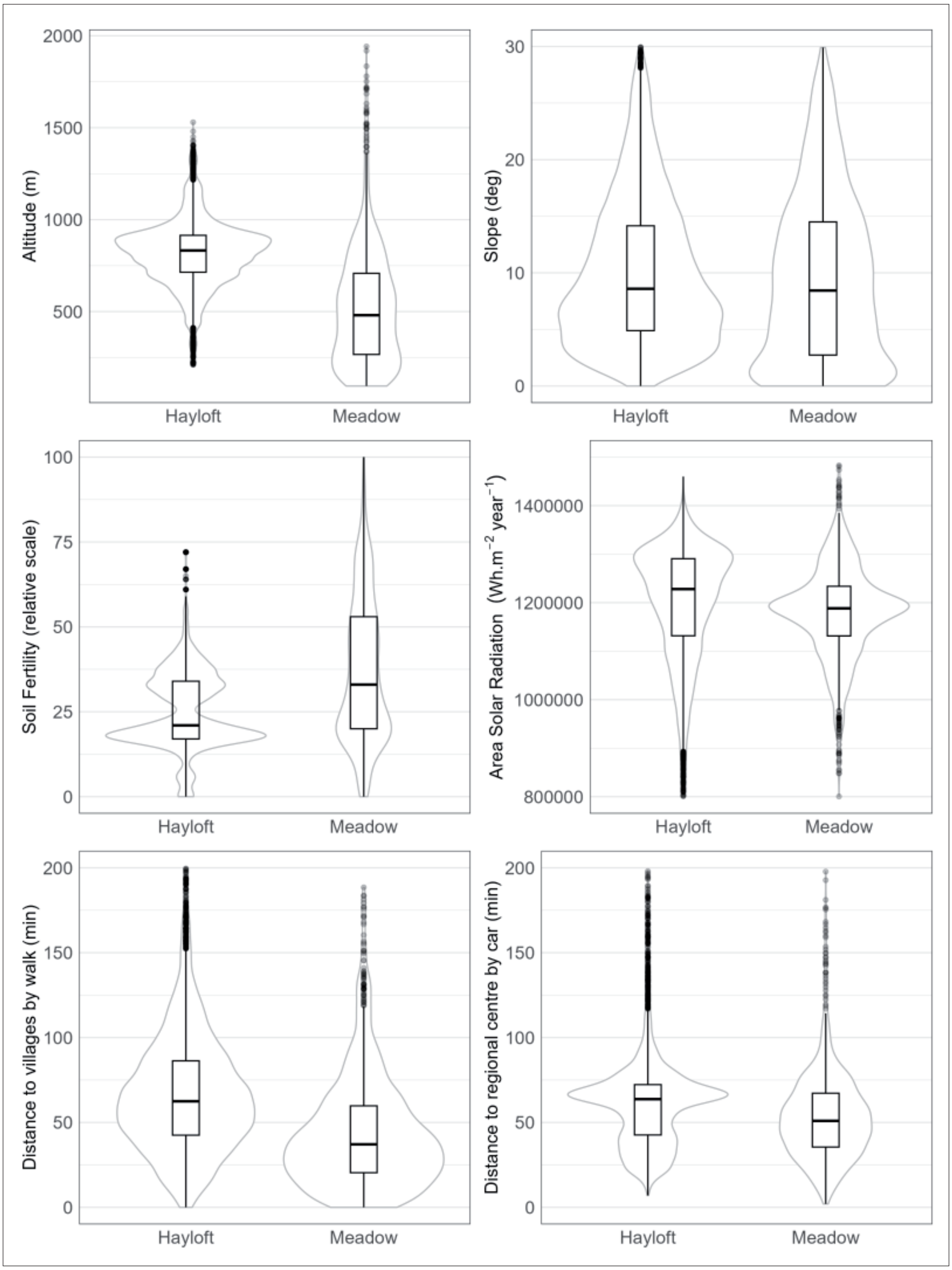

Fig. 4: Diagrams showing the differences in influence of selected factors between the hayloft localities and meadows
Source: Authors' elaboration

half of former hayloft localities (51.17%) were changed during the past 70 years. A large part of the sites is overgrown by forest or is in various stages of succession. Some of the former hayloft meadows have been converted into arable land. Changes related to urbanisation were connected with enlargement of settlements, creation of recreational sites, or to a lesser extent, to water bodies (hydroelectric power plant, water reservoir and ponds), roads, or industrial areas (Fig. 5).

4.4 Current state of preserved haylofts in the Upper Liptov region

During the field survey, the haylofts of Upper Liptov region that have survived to date were recorded (see photos on Fig. 6). Out of 74 wooden features originally identified from recent aerial photographs, 48 were haylofts. The remaining objects were ruins of winter stables (at villages of Vyšná and Nižná Boca), cottages or barns.

Most of the recorded haylofts were roofless, or collapsed, in most cases with shrubs growing inside, or outside the walls. We also identified preserved haylofts, which no longer fulfil their original function of storing the hay, but are used for different purposes, such as buffet for skiers located on the ski slope (one hayloft), recreational cottage without water and electricity (one hayloft), or for storage as sheds (three haylofts). Quite a number of preserved haylofts had a shingle roof covered with metal sheeting, which prolonged their life. Only in five cases, we found haylofts with preserved original shingle roofs (Tab. 2).

The surrounding land was used in 35% as mowed meadows, or pastures for cattle, 13% were recently abandoned (grasslands without non-forest woody vegetation), and in 6% their immediate surroundings were rebuilt. Almost half of the surrounding land undergoes succession, when 38% of sites are abandoned and overgrown by shrubs and 6% of sites are already covered by forest. Several areas of the former hayloft meadows are currently under pressure from the construction of recreational cottages (see Fig. 7).

5. Discussion

5.1 Using the historical topographic maps for mapping the haylofts

We used historical topographic maps from 1952–1957 to identify historical distribution of haylofts on hay meadows in Slovakia, which captured the situation before the collectivisation largely. Altogether, in the 1950s, we identified 9,742 haylofts, localised in the cadastres of 161 municipalities, out of which in 25 cadastres the process of collectivisation started already, as newly established cooperative farms were identified together with haylofts. Therefore, it can be assumed that in these areas there may have been more haylofts, which may have already been removed due to intensification processes during collectivisation (such as land consolidation, removal of non-forest woody vegetation and haylofts, drainage, and reploughing and reseeding of grass species.

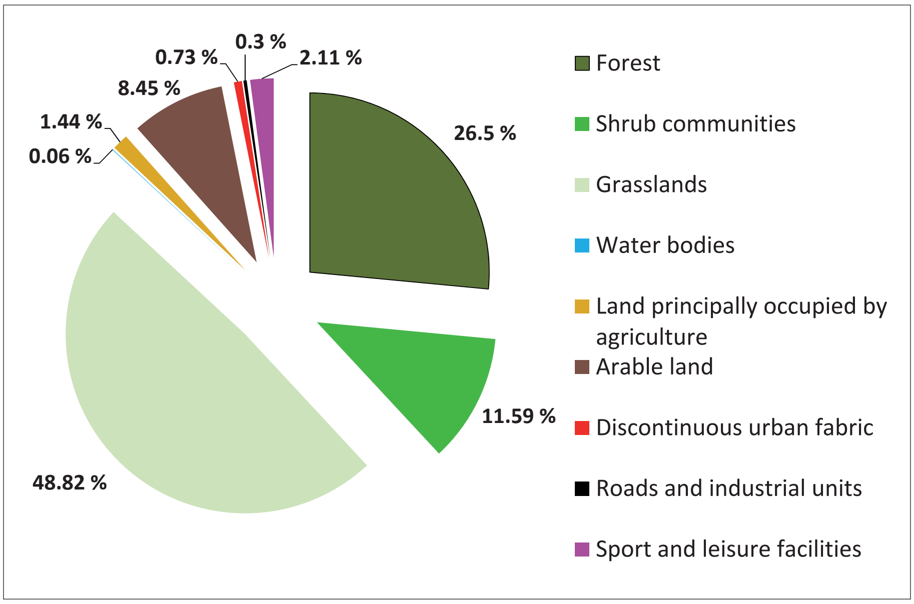

Fig. 5: Current land cover of former hayloft localities
Source: Authors' elaboration

Fig. 6: Example of different stages of decay of haylofts in the Upper Liptov Region – from left to right: (a) Preserved hayloft in a complex of hay meadows with high biodiversity in Liptovská Teplička – type I.; (b) Damaged hayloft in the cadastre of the Nižná Boca – type II.; and (c) Remnants of the hayloft in Nižná Boca – type III
Photos: Z. Baránková (2023)

Haylofts			Surrounding landscape						
Type of preserva-tion	Current use	Condition of haylofts	Meadow	Pasture	Overgoing succession with shrubs	Overgoing succession with shrubs and trees	Urbanisation	Recently without agri-cultural use, without shrubs and trees	**Total**
I	No	Preserved with original shingle roof	2			1		1	**4**
		Preserved with repaired tin roof	2			1		4	**7**
		Preserved as a cottage					1		**1**
	Yes	Preserved with original shingle roof		1					**1**
		Preserved with repaired tin roof	3						**3**
		Preserved as a cottage	1						**1**
II.	No	Damaged shingle roof		1			1		**2**
III.	No	Shrubs inside, collapsed roof and partially damaged side timbers	1	3	11	1	1	1	**18**
		Shrubs inside, collapsed roof, side timbers preserved	2	1	6				**9**
		Shrubs inside, traces only			1	1			**2**
Total			**11**	**6**	**18**	**4**	**3**	**6**	**48**

Tab. 2: The present state of haylofts and use of surrounding landscape
Source: Authors' elaboration

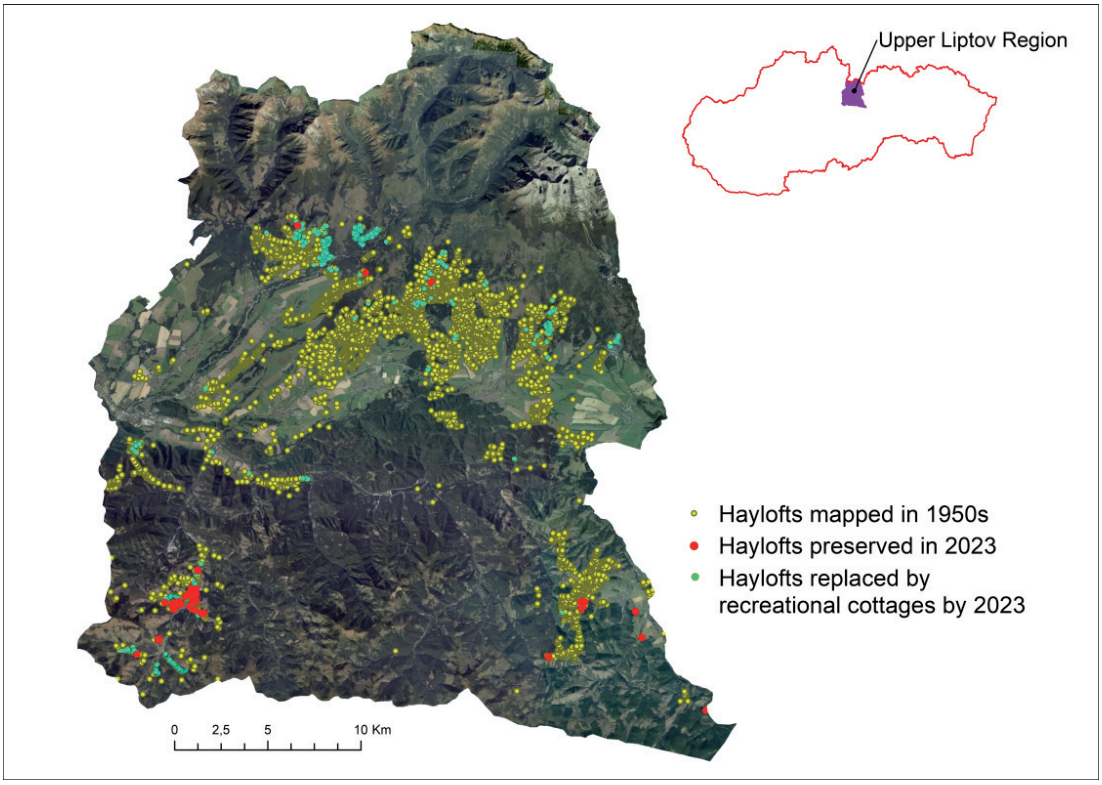

Fig. 7: Distribution of identified haylofts and recreational cottages in the Upper Liptov Region in 2023
Source: Authors' elaboration

Despite this, the topographic maps that were used represent the best historical source for identifying haylofts for the large-scale study in contrast to cadastral maps that can be used for local or regional studies. Moreover, the haylofts on the maps can be easily distinguished from other buildings in the countryside (sheds, outbuildings, but also houses in areas with dispersed settlement) on the base of their clear designation and labelling. As for the other sources on the historical distribution of haylofts, we can use the maps of the first Austrian military mapping (1763–1787), the second Austrian military mapping (1806–1869), both at the scale of 1:28,800 and the third Austrian military mapping (1857–1883) at the scale of 1:25,000 (Timár et al., 2011). According to these maps, the haylofts were already present in the area, but the presence of haylofts was marked schematically and does not give a realistic image of their real numbers.

5.2 Geographical conditions related to haylofts distribution

Altitude is an important geographical factor related to various environmental gradients like temperature, moisture, wind and also human land use (Körner, 2007). Hayloft meadows in Slovakia were predominantly situated in areas at elevations ranging from 700 to 900 metres, because lowlands in Carpathian areas were historically transformed to agricultural fields (Munteanu et al., 2014; Lieskovský et al., 2018) and most of the grasslands remained in submountain and mountain areas. Elevation and slope representing terrain were also the most important variables determining grazing localities in Europe, except in the Mediterranean South (Malek et al., 2024).

Significant role of slope steepness in landscape development was confirmed in various studies from Europe (MacDonald et al., 2000; Giampaolo et al., 2012; Opršal et al., 2013; Bajocco et al., 2016) and Slovakia (Lieskovský et al., 2015; Masný et al., 2017; Pazúr & Bolliger, 2017). Our study shows that most of the haylofts were located on moderate or moderately steep slopes ranging mostly from 5 degrees (1st quartile) to 14 degrees (3rd quartile), which is in line with other studies (Robert, 1942; Podolák, 1962). However, we found that slope steepness did not play a significant role in hayloft location in comparison to other grasslands.

Distance of haylofts from nearest settlements was higher in comparison to other meadows. The hay meadows (the so-called back meadows) were located in remote areas and hay was stored in haylofts located on those meadows. This was the main difference from the meadows located closer to the village (the so-called front meadows), which were mowed twice a year, and the hay was transported to the barns in the village. By tracking "walking distance", we confirmed and quantified the average distance of these meadows from the villages, and also differentiated them from other meadow types. Higher distances from the nearest settlements are also associated with abandonment of agricultural land (Prishchepov et al., 2013; Fonji & Taff, 2014; Malek & Verburg, 2020). Isolated communities rely more on self-sufficiency (Renes, 2014), which could be also related to hay meadows. In addition, the isolation prevents modernisation and determines persistence of traditional agriculture (Solymosi, 2011), because farmers see traditional systems as a barrier of modernisation through mechanisation (Eichhorn et al., 2006).

Haylofts were built on meadows with lower soil quality compared to other grasslands. In general, the meadows were medium-productive, and their fertility was increased by mowing or fertilising with manure or wood ash. On the lowest quality soils (often in high altitudes), pastures were located. The rich, fertilised meadows mown twice a year were located near villages and more remote, less accessible sites hosted single-cut grasslands and in some regions with location of haylofts (Podolák, 1961). Here the rotation of mowing and grazing (meaning also fertilisation) was applied and formed a transition to the foothill pastures (Halada et al., 2008). The alternating mowing and grazing of hayloft meadows is evident also on the military topographic maps from 1950s, where haylofts are recorded on meadows, but also to a lesser extent on pastures (Fig. 2), or occasionally even on field margins. The combination of mowing and grazing was traditional practice of hay meadows management also in other parts of the Carpathians and this system is today highlighted as a practice supporting grasslands conservation and restoration (Dmytrash-Vatseba & Shumska, 2020; Janišová et al., 2023).

The macroclimatic factors as annual average temperature or precipitation are highly correlated with altitude; therefore, we selected the annual solar radiation for the representation of microclimate parameters. It is the factor with the greatest influence on hay drying (Rotz, 1993). The haylofts were preferably built on areas with higher solar radiation. The hay from hayloft meadows was stored for longer periods, and so there was a need to ensure good quality drying of the hay. This was assured by locating the haylofts in sunny areas.

5.3 Current state of haylofts and land cover changes of hayloft meadows

Central and Eastern Europe has been one of the global hotspots of agricultural land abandonment in recent decades (Kuemmerle et al., 2016; Munteanu et al., 2017; MacDonald et al., 2000). Marginal mountain areas were more prone to abandonment (Kuemmerle et al., 2008; Pazúr et al., 2020), which is in line with our study. Almost 38% of sites have been influenced by abandonment and have changed to forest or shrub communities. The change of permanent grasslands into shrub and forest associations as the most important change of farmland was confirmed also from other Slovak regions (Šebo & Kopecká, 2014; Feranec et al., 2017). On the other hand, 11% of the sites have been modified by intensive human activity (construction of cottages, conversion to arable land, construction of motorway, etc.). The level of abandonment of former hayloft localities can be also indicated according to the stages of hayloft decay. Kušar and Komac (2019) presented a classification of the levels of decay of haylofts, which they used as an innovative indicator of changes in the cultural landscape. By using a simplified version of this classification, we observed almost 65% of the haylofts in different stages of deterioration.

Detailed field research in the Upper Liptov Region shows that only 1% (48 haylofts) of the original haylofts has been preserved and most of them are in different stages of decay. Preserved ones are not used for storing hay anymore. This is in line with the overall decline of traditional farming in Slovakia. Less than 2% of traditional agricultural landscapes survived collectivisation of agriculture (Lieskovský et al., 2014) and half of them are in the different stages of abandonment (Lieskovský et al., 2015). Abandonment of traditional agricultural practices and associated loss of biodiversity, ecological knowledge, biocultural (Agnoletti & Emanueli, 2016; Baránková & Špulerová, 2023) and other values is an ongoing worldwide issue (Tarolli et al., 2014; Varotto et al., 2018; Vasilescu et al., 2023).

In addition to the analysis of the geographical factors under which hay meadows were formed, future research should also be extended to sociological characteristics and historical settlement development, which most likely also played a significant role in the location of hayloft meadows in Slovakia. Another important issue is the high biodiversity value of former hayloft meadows (Ružičková & Kalivoda, 2007) and impact of current environmental schemes, the extent to which they contribute to the conservation of species-rich, semi-natural hay meadows.

6. Conclusions

Former hayloft localities differed mainly in geographical conditions related to altitude and soil fertility compared to other grasslands. More than 50% of the sites are now overgrown with forests or undergoing succession processes. Their rich historical legacy is, to a small extent, still evident today through the preservation of haylofts as witnesses to traditional farming. However, only 1% of them have survived in the study area, from which, most of them have deteriorated. They are no longer used for hay storage, but they are sporadically used as sheds, cottages, or as a shelter for skiers. The haylofts, together with traditional species-rich hay meadows with high biodiversity created the traditional landscape scenery and can be considered as valuable biocultural heritage of Slovakia related to agricultural landscape, which has almost disappeared. The question of preserving the last remnants of hay meadows is therefore very current, and ways to preserve them should be sought, for example within agri-environmental schemes.

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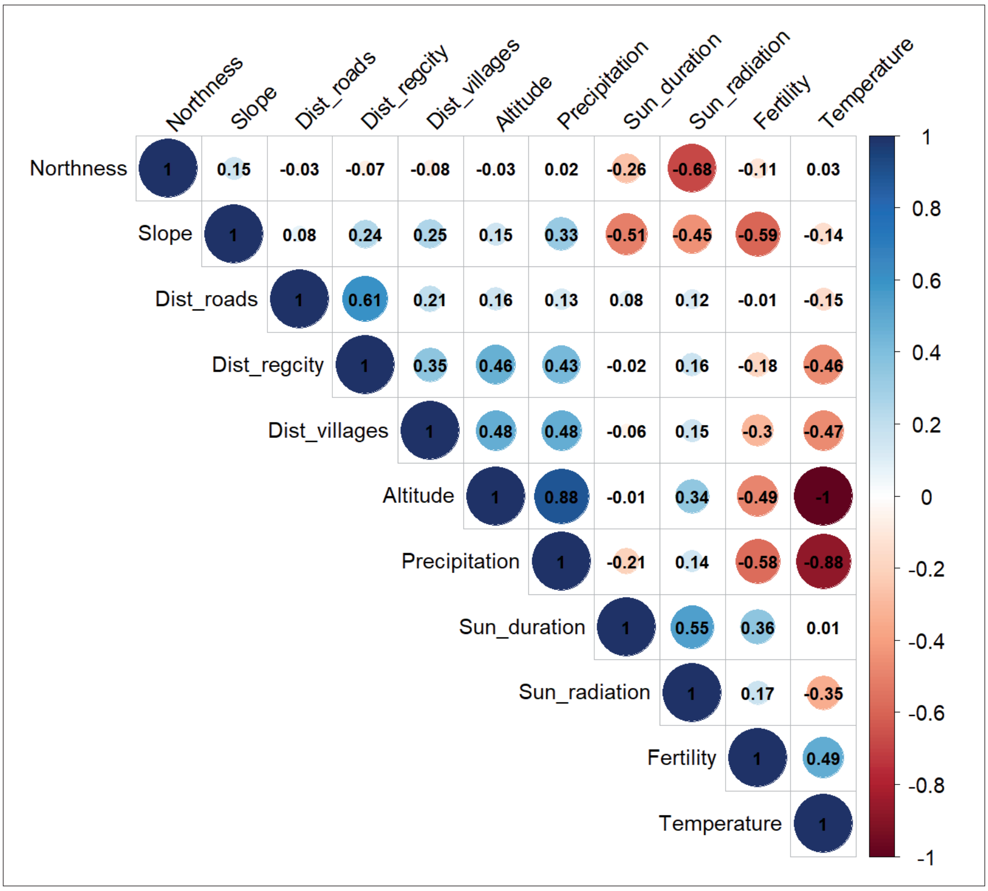
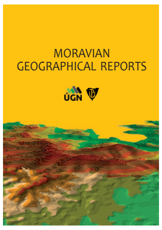
Appendix



Appendix 1: Correlation analyse of selected variables

- *Northeness: Cosine of aspect (in radians)*
- *Slope: Slope steepness (degrees)*
- *Dist_roads: Distance to roads (meters)*
- *Dist_regcity: Distance by car to regional centre in minutes*
- *Dist_villages: Walking distance from nearest settlement in minutes*
- *Altitude: Altitude (meters above sea level)*
- *Precipitation: Monthly means of rainfall (1990–2000)*
- *Sun_duration: Time of sunshine duration (incorporated effect of hill shading) in hours per year*
- *Sun_radiation: Average amount of solar energy received from the sun per year (Wh.m^{-2})*
- *Fertility: Soil production potential derived from soil type, slope steepness, aspect, skeletal content and depth, grain size distribution, and climate factor (relative scale)*
- *Temperature: Monthly means of temperature (1990–2000)*



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Using the Relative Elevation Models to delimit the floodplain level development: The case of the braided-wandering Belá River, Slovakia

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Abstract

The Belá River is a specific submountain river running through the Liptov Basin in the Slovak Carpathians. Its transformation from a braided to a braided-wandering system and degradation including incision of the river system has been observed since the middle of the 20th century. These processes have created a complex system of floodplains with development stages. For their identification, the Relative Elevation Model normalizing absolute floodplain elevation to the river channel changes has been established. Three models have been prepared, from the channel bottom and water level elevation gauge by GPS, and the water level elevation by LiDAR. Based on the resulting models, the floodplain was identified and delineated to an active or potentially active floodplain, to an inaccessible floodplain spread behind artificial structures, and to a perched floodplain beyond the reach of the river. Spatial statistics, including "Hot spot analysis" and "Cluster and outlier analysis" have been used to identify recent river floodplain formation from 1949 to 2018, caused by simplification and incision of the Belá River. The unique aspect and contribution of the research lies in implementing and comparing the Relative Elevation Models and linking them to floodplain age.

Keywords: *Floodplain, floodplain delimitation, floodplain development, Relative Elevation Model, braided-wandering river, Belá River*

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1. Introduction

The Belá River is a typical example of a braided-wandering river, with a high gradient and huge and irregular sediment input. During the last decades, the river has been affected by transformation and degradation of the river pattern. The process has been unevenly accompanied by narrowing, shifting and incision of the braidplain due to decreasing discharge, reducing extreme floods and land cover changes. As a result of the processes, floodplain levels have been formed, with different relative heights to the river channel. However, their distribution and position along the river are not proportional. The novelty of the publication lies in the generation of Relative Elevation Models (REMs) based on the various input data, and combined with aerial photographs, this method has the potential to capture the trend and enable prediction of the river floodplain development. Therefore, the objectives of the study are:

i. To generate the Relative Elevation Models;
ii. To compare and evaluate the models and the used method;
iii. To identify and highlight the levels and development stages of the river floodplain; and
iv. To evaluate a process-oriented model of the river floodplain development.

The determination of various floodplain stages and definition of a process model of the floodplain development will primarily depend on the quality and interpretation of the REMs.

2. Theoretical background

The river floodplains, stretching along the watercourses as products of fluvial activity, represent a unique and unmistakable feature of the landscape. They are distinctive not only by their ecological but also by geomorphological characteristics, they provide records of previous river behaviour and changes. A river floodplain is a relatively flat area developed from alluvium, extending from the river banks and periodically inundated (Huggett, 2011). Nevertheless, definitions can vary based on different approaches or principles of delimitation (Rhoads, 2020). As well as definitions, a research of river floodplains has been focused and applied in diverse directions, based on floodplain delineation (Lóczy et al., 2012), level development (Kiss et al., 2017), management (Olson et al., 2014; Croke et al., 2016; Jakubínský et al., 2021), restoration (Eder et al., 2022), or ecology (Gray & Harding, 2007; Hauer et al., 2016).

Generally, the floodplain is formed and reworked by different river processes, mostly migration and accretion (Brierley & Fryirs, 2005), described by evolution models (Bollati et

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al., 2014). The formation of a river floodplain along the braided rivers creates mosaics of multi-aged floodplain units by the migration and accretion of the braidplain, easily determined by aerial photographs (Haschenburger & Cowie, 2009). Beechie et al. (2006), used vegetation for floodplain age assessment, where the age classes of a floodplain varied from 5 to 25 years, with a mean 8-year erosion return period. The floodplain along the Waimakariri River in New Zealand has a 250-year return period based on the dendro-chronology, field observations and time-lapse of aerial photographs (Reinfelds & Nanson, 1993). Determining the age of the river floodplain based on the former position of the river (Greco et al., 2007; Whited et al., 2007) is a more reliable method for the determination of the floodplain stage (Haschenburger & Cowie, 2009). Specifying the position of the channel (Ziliani & Surian, 2012) should enable a prediction of possible future channel movements and thus better prevent any negative consequences of these shifts (Marti & Bezzola, 2006).

The lateral shifting and channel migration are variable in time and space, resulting in uneven input, accumulation, and erosion of material from the river channel and river floodplain. Therefore, the river floodplain has an asymmetrical character, with longitudinal and lateral differentiation, creating perched floodplains (Lehotský et al., 2015). The contrast is even more distinguishable along braided rivers (Lehotský et al., 2018). A height differentiation of the river floodplain can be affected by climate change or by land use changes (Kadlec et al., 2009) affecting the hydrology (Zaprowski et al., 2005). The climate changes strongly and irregularly affected the discharges of the water streams across the Europe (Blöschl et al., 2019). The braided rivers are susceptible to discharge changes (Hajdukiewicz et al., 2018; Nardi & Rinaldi, 2015), or human impact (Gurnell et al., 2009) which strongly affect mountain streams (Wohl, 2006). Therefore, the last century led to the transformation and degradation of the mountain streams (Armaş et al., 2013; Rădoane et al., 2013; Dufour et al., 2015; Krzemień et al., 2015; Nardi & Rinaldi, 2015; Wyżga et al., 2016). Channel incision can affect the level of the groundwater table (Greco et al., 2008), and the connection between the channel and the river floodplain (Lehotský et al., 2018).

A river development process led by incision can generate floodplain level formation and can possibly be described by cross-section profiles (Kiss et al., 2017). LiDAR (Light Detection and Ranging) and its different height classification intervals enable the identification of forms in the vicinity of the waterstream (Moretto et al., 2012). The Relative Elevation Model (REM) provides a different view of the floodplain for the floodplain delimitation, identification or other analyses. The height above river (HAR) model (Jones, 2006) was used to identify side channels on a floodplain by digitizing lines across the floodplain with an elevation of a water surface. The water surface was subsequently subtracted from a standard Detail Terrain Model (DTM). Dilts et al. (2010) pointed out a problem in how to generate the cross-section properly, to uniformly capture the river floodplain. They used ArcGIS Spatial Analyst to implement the Kernel Density and Cost-distance function, to calculate inundation areas and a bathtub model. The Kernel Density was modified by Olson et al. (2014) and compared with an IDW method and Cross-section method. Greco et al. (2008) used a channel water surface during the dry season base flow and subtracted it from topographic maps, using the IDW method.

The cross-section method yields valuable results but requires the largest effort level. Similarly, Slaughter and Hubert (2014) visualized features on a floodplain, by adjusting the elevation of the river to the initial elevation level, removing downstream changes in elevation related to the channel gradient. Besides, Coe (2016) modified previous methods and simplified them. Dilts (2015) provides an automatic ArcGIS toolbox, useful for quick HAR model generation. The Toolbox quickly and easily identifies changes in elevation on the floodplain across the river channel but with lower resolution output. According to Greco et al. (2008), the relative elevation model has huge potential for studying rivers and floodplains in combination with other attributes of the river. The proper method for such visualization could be challenging. However, the above mentioned studies presented models generated from water levels, and no study generated such a model from the river bottom or compared the models.

3. Data and methods

3.1 Study area

The Belá River (see Fig. 1) has a notable place among the Slovak rivers because of its specific dynamic of braided-wandering channel planform. It arises in a submontane area of the High Tatra Mountains and after 23.6 km flows into the Váh River. The catchment area is 244 km^2, with average temperature from 4 to 8 °C and average annual precipitation from 550 to 1,200 mm. Historically, the braided river system gradually changed and transformed into a braided-wandering river system during the second half of the 20th century (Kidová & Lehotský, 2012). The most significant factors of morphological changes are land cover changes and discharges (Fig. 2) (Kidová et al., 2016a), which degraded the multi-temporal river system as a consequence of sediment volume decreasing from the floodplain and upper part of the river (Lehotský et al., 2018). Two gauging stations are localized at Podbánske (922.72 m a. s. l.) and Liptovský Hrádok (359.3 m a. s. l.) with an average annual discharge of 3.5 $m^3.s^{-1}$ and 6.8 $m^3.s^{-1}$, respectively (Kidová & Lehotský, 2013). The extreme flood events are represented by discharges higher than 60 $m^3.s^{-1}$ (Kidová et al., 2016b). The largest flood events appeared on 18.07.1934 (179 $m^3.s^{-1}$) and 29.06.1958 (180 $m^3.s^{-1}$), but extreme floods and discharges gradually decreased (Kidová & Lehotský, 2012) which affected channel pattern changes (Kidová et al., 2016a, 2016b). The Belá River is affected by no dam regulation.

Land cover changes, human impact (Kidová et al., 2016b) and gravel mining (Radecki-Pawlik et al., 2019) strongly affected the channel transformation process. Channel engineering of the river channel and its surroundings was constructed to protect settlements against flood events and to stabilize the river channel (Kidová et al., 2021). However, it caused an incision of the channel, increased the local erosion base and accelerated landslides (Kidová et al., 2016a). The heaviest anthropogenic impact affected the lower part of the river, decreasing upstream (Kidová et al., 2016b). The first systematic flood control management appeared from 1925 to 1948 and it led to reducing the floodplain area (Kidová, 2010). In 2000, a small hydropower plant was built which heavily affected local part of the river channel and resulted in hungry water eroding the riverbed upstream (Kidová & Lehotský, 2013). Furthermore, land cover changes brought the sediment volume variation which led to the incision of the river (Kidová & Lehotský, 2012) as a result of forest cover area transformation (Kidová et al., 2016a). The incision caused by the processes described above has disconnected the river channel and the floodplain (Lehotský et al., 2018).

3.2 Data

Three types of data were used in the paper, including (1) the orthophoto mosaic, (2) the LiDAR data, and (3) the terrain survey data. The orthophoto mosaic was provided by the Geodesy, Cartography and Cadastre Authority of the Slovak Republic (ÚGKK SR), capturing the area of the Belá River in 1949, 1961, 1973, 1986, 1992, 2003, 2006, 2009, 2012, 2015 and 2018. The point cloud was collected from 2018 to 2019 by ÚGKK SR, with

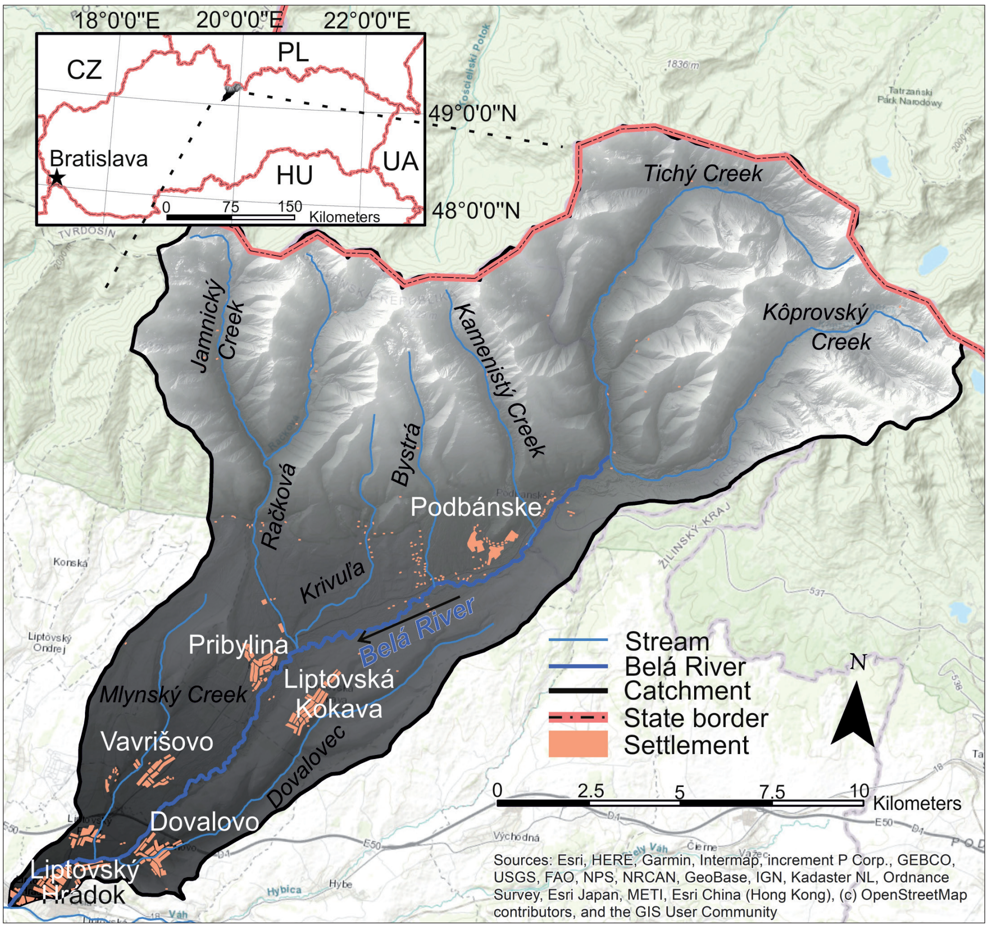

Fig. 1: The location of the Belá River study area in the northern part of Slovakia, represents an unmistakable component of the piedmont Carpathian region. The Bela River is strongly influenced by numerous right-side tributaries, dominating over the left-side tributaries. Simultaneously, with a significant anthropogenic intervention in the lower part of the catchment, they significantly disturb the gradient of the stream. The left side of the river is confined by terraces, strongly limited in its lateral movement.
Source: Authors' elaboration

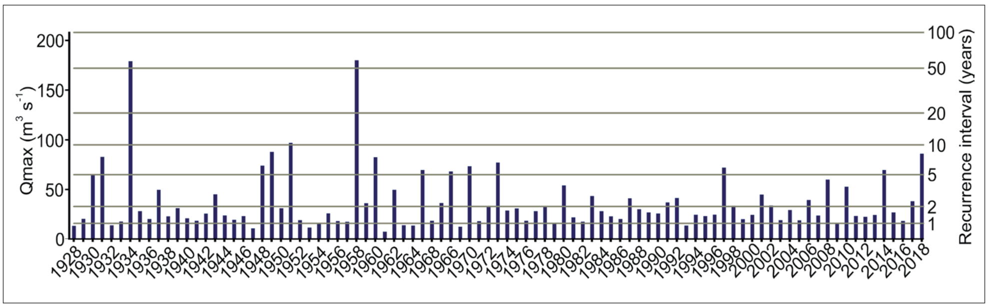

Fig. 2: The maximum annual discharges at the Podbánske gauging station. The extreme flood events are decreasing, affecting the river behaviour, and subsequently the river floodplain development.
Source: Authors' elaboration based on data from Slovak hydrometeorological institute (SHMÚ)

a horizontal accuracy of 3 to 4 cm and a vertical accuracy of 7 to 17 cm. The upper locality has the designation 26_Tatry and the lower 25_Ružomberok. Altogether 34 footprints of point clouds were used (Tab. 1). The terrain data were collected in 2017 and 2018 by GPS Leica Zeno with aerial GG03s with RTK corrections 2–11 cm. The terrain data consisted of 358 points of water level and 364 points of channel bottom in the longitudinal profile. For analyses, we pick 44 points, approximately every 500 m along the floodplain centreline.

3.3 REM formation

Firstly, from the LiDAR point cloud data, the DTM with 1 m resolution was generated, necessary to identify and delineate the river channel and river floodplain edges. The floodplain was perceived as an alluvial landform spread from the banks of the river to the edge of the adjacent terraces, in terms of the genetic floodplain by Nanson and Croke (1992). The floodplain boundary was determined as a slope and elevation change between the considered floodplain and the lower edge of the terrace based on the DTM. The changes in elevation between the terrace and the floodplain often reached more than 30 m. On the other hand, elevation differences between the perched floodplain and the active floodplain were generally less than 2–2.5 m, and they are harder to distinguish (Fig. 4). Moreover, it is still possible to identify remnants of fluvial activity on the perched floodplain from the DTM or from the orthophoto mosaics (1949, 1961, 1973). A geological map of Slovakia (Geologická mapa Slovenska, 2023) can distinguish floodplain fluvial sediments from terraces and orthophoto mosaic (ÚGKK SR) supports the identification of floodplain edges in indistinct locations.

Locality	Number of footprints	Date of footprinting	Time of flying (round on the hours)	Podbánske ($m^3.s^{-1}$)	Liptovský Hrádok ($m^3.s^{-1}$)
26_Tatry	10	10.06.2018	06:00–08:00	5,317–5,370	8,806–8,806
	4	12.09.2018	10:00–12:00	2,384–2,385	3,354–3,458
25_Ružomberok	2	19.11.2019	11:00–12:00	5,827–5,847	8,799–9,305
	17	24.11.2019	10:00–14:00	4,317–4,354	7,243–7,522
	11	25.11.2019	09:00–16:00	4,075–4,140	7,243–7,522

Tab. 1: The LiDAR footprints were used to create the DTM, overlaying the riverbed of the Belá River. The table contains the code designation of the area, the number of footprints in the given area, the date and time of recording, and the variation of discharges (in $m^3.s^{-1}$) during the given periods at the Podbánske and Liptovský Hrádok gauging stations
Source: Authors' conceptualization based on data from the Geodesy, Cartography and Cadastre Authority of the Slovak Republic

Secondly, the floodplain was divided into 500 m wide cross-sections based on a Fluvial Corridor Toolbox (Roux et al., 2015), perpendicularly on a streamline (Fig. 3). Afterwards, each cross-section was attributed with the water level elevation (lowest point from gravel on a channel bar) derived from the LiDAR/DTM, along with the water level and bottom elevation measured by GPS in the field. The values were separately interpolated to the whole floodplain area by the "Topo to raster" interpolation as contours, with 1 m resolution and with other default settings. Afterwards, the raster was subtracted from the original floodplain DTM in ArcGIS 10.5. "Topo to raster" interpolation was chosen based on the most accurate results at floodplain margins and at greater distance from the channel, compared to other interpolation methods, including Dilts (2015) automatic toolbox. Normalized rasters of the Relative Elevation Model (REM) represent the results of the model.

3.4 Delineation of floodplain

The floodplain was delineated based on the REM into three groups, including: (1) an inaccessible floodplain (floodplain with no inundation caused by artificial structures such as dikes or roads), (2) a perched floodplain (an inaccessible floodplain with no inundation caused by incision of the river), and (3) an active or potentially active floodplain. First, the inaccessible floodplain was delineated. The dikes and roads were easily identified by the orthophotos and the REMs, protruding above the surroundings. The floodplain from those structures to the edge of the terraces was understood as the inaccessible floodplain. The remaining floodplain was divided into the perched and active floodplain. Identification of, and distinguishing between, active and perched floodplain using only DTMs or Hillshade were unclear and problematic (Fig. 4). However, using the REM it is possible to identify the perched floodplain quickly and accurately. The changes in the elevation of the river floodplain relative to the channel could be several meters, recognizable in the cross-section profile. The perched floodplain was considered a higher continuous part of the genetic floodplain, mostly boldly separated by high or sharp edges. The rest of the floodplain was considered an active or potentially active floodplain.

3.5 Spatial statistics

The age of the floodplain was determined by the overlapping position of channels based on the method of Greco et al. (2007). The river channel was delineated by the definition of Lehotský et al. (2015), as including gravel bars, but without river islands. The river islands presented potentially stable parts of the braidplain and floodplain. Accumulation of alluvium between two following years, minus erosion of subsequent years, represents the age of the floodplain. The study is represented by aerial photographs from 1949, 1961, 1973, 1986, 1992, 2003, 2006, 2009, 2012, 2015 and 2018. The volume of deposited fluvial material does not have uniform distribution over time, moreover, channel incision and river training affect the river channel and its surroundings. These processes could result in floodplain levels formation. The identification of the changes was based on spatial statistics of the floodplain mosaic. The null hypothesis for the pattern analysis was, that there is no spatial pattern of floodplain formation in the study area.

Using the "Zonal Statistic as Table" tool in the "Spatial Statistic" ArcGIS, the MEAN value from the REM was calculated for each polygon representing a particular river floodplain age. The distribution of polygons with their relative height can vary, be dispersed or clustered. The Global Moran's I by the "Spatial Autocorrelation (Moran's I)" represents how features (polygons) differ in the study area (Mitchell & Grifin, 2021). The next step was to find the hot spots and cold spots of the spatial distribution of polygons with relative elevation height mean values by a "Hot Spot Analysis (Getis-Ord Gi*)". The Gi* statistic reveals, if there is or is not a concentration of high or low values. The result was compared to the "Cluster and Outlier Analysis (Anselin Local Morans I)", to find clusters of high and low values. Eventually, areas with concentrations of high and low values were analyzed. The polygons with the high values (hot spots) represented the parts of the newly formed floodplain created by the incision of the river and the low values represented the floodplain formed due to simplification, narrowing and side channel abandonment. A process-oriented model of river floodplain development was the outcome of this analysis.

4. Results

4.1 The REM settings

The elevation of the floodplain along the 23.6 km long Belá River on the DTM rises from 626.49 m a. s. l. to 985.08 m a. s. l., but the values do not reflect the relative elevation to the water stream. The Relative Elevation Models (REMs), a normalized

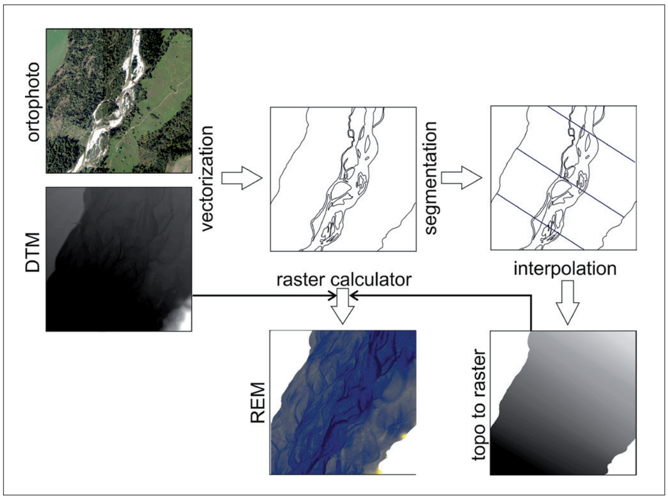

Fig. 3: The method of the Relative Elevation Model generation. The floodplain and channel position (in 2018) were delimited based on the orthophotos and DTM. The cross-sections were created every 500 m perpendicularly on a floodplain centreline. The value for every cross-section was subtracted and subsequently interpolated as a water level raster, and then the raster was subtracted from the original DTM. The process was accomplished for DTM and GPS water level and river bottom. The result of the processes were the REMs
Source: Authors' conceptualization

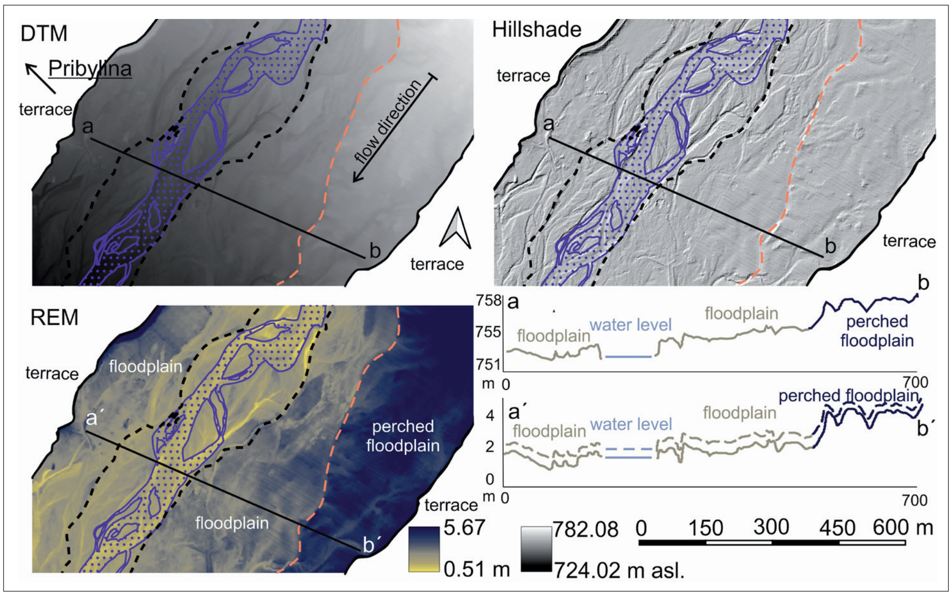

Fig. 4: A floodplain visualization near the Pribylina settlement by the DTM, its Hillshade and the REM. The area with blue dots symbolizes the river channel position in 2018, black dot lines are a historical extension of braidplain. The active floodplain and perched floodplain were identified, and distinguishable on REM. The cross-section a-b represents the profile of the floodplain generated from DTM. The cross-section a'–b' represents two REMs profiles. A solid line represents a profile normalized to the channel bed, and a discontinuous line represents a profile normalized to the water level
Source: Authors' conceptualization

DTM to the water stream, decreased the range of the values (see Tab. 2). For the research, three REMs were generated utilizing: the DTM water level (REMwater^{DTM}), the water level measured by GPS (REMwater^{GPS}), and the channel bottom measured by GPS (REMbottom^{GPS}). The difference in mean value between REMwater^{DTM} and REMwater^{GPS} was 0.02 m, and their minimum and maximum differences fluctuated by 0.02 m. The range of the values was almost identical (Fig. 5) which confirms their similarity. The mean difference between two REMs generated from GPS (REMwater^{GPS} and REMbottom^{GPS}) was 0.51 m, corresponding to a mean water level in the river channel represented 0.48 m. Thus,

	DTM	REMwater^{DTM}	REMwater^{GPS}	REMbottom^{GPS}
Min.	626.49	– 2.18	– 2.20	– 1.83
Max.	985.08	16.04	16.02	16.52
Mean	759.62	2.16	2.14	2.65
Range	358.59	18.22	18.22	18.35
Std.	91.11	1.44	1.44	1.44

Tab. 2: The basic characteristics of the river floodplain are represented by DTM and three REMs
Source: Authors' conceptualization

REMwater^{DTM} and REMwater^{GPS} show high similarity, and the difference between REMwater^{GPS} and REMbottom^{GPS} represents the difference in water level and channel bottom elevation.

The distribution of river floodplain values on the DTM (Fig. 5) primarily follows the width of the river floodplain, which widens distinctively twice at the mouth of the Váh River in the lower part (pixel values from 620 to 700), twice in the vicinity of the Podbánske settlement (pixel value from 710 to 850 m), and narrows considerably in the upper part in the surroundings of the Pribylina settlement. On the other hand, the REM represents the distribution of values indicating the average height of the floodplain along the river stream, comparing the stream bottom or the water stream level. Floodplain elevation normalized to channel, redistributed the elevation values, and decreased the mean value of floodplain elevation.

4.2 Floodplain delimitation

The floodplain along the Belá River has a total area of 9.364 km^2 with irregular width (from 60 m to 1,000 m) and an elevation range of 358.59 m a. s. l. However, a significant part of the floodplain is situated behind the dikes or road embankments, creating an

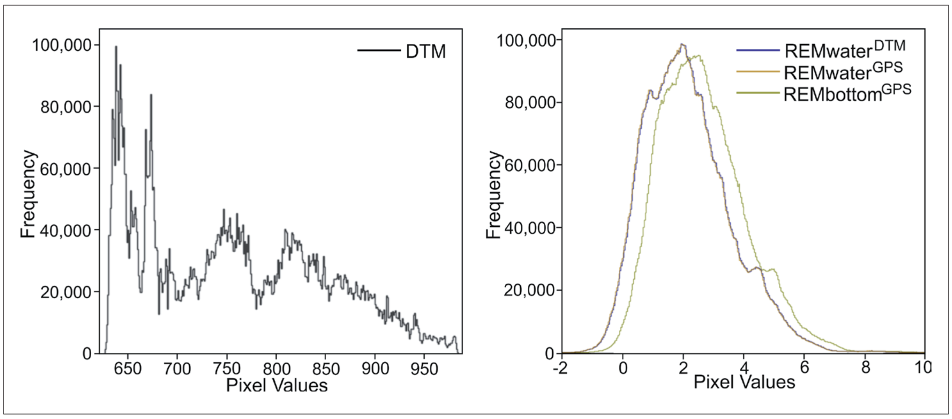

Fig. 5: The distribution of elevation values of the Belá River floodplain expressed by the DTM (left) and three REMs (right). The value distribution of REMwater^{DTM} and REMwater^{GPS} are nearly identical
Source: Authors' elaboration

isolated floodplain. The inaccessible floodplain represents 31.6% (2.961 km^2) of the entire topographical floodplain. The largest part of the inaccessible floodplain is situated along the lower part of the river along the Liptovský Hrádok, in the places with dikes construction, and in the higher part, where the roads intersect the floodplain (Fig. 6). The relative height of the inaccessible river floodplain ranges from 0 to 6 meters (Fig. 7).

The perched floodplain was especially detached, representing 2.767 km^2, or 29.5% of the topographic floodplain. They represent the continuous surfaces of the river floodplain, considerably higher than the river channel and surrounding floodplain, mostly with sharp edges. There were no critical height differences, but most of the perched floodplain was higher than 2.5 m above the channel bottom. The histograms represent the values from 1.5 m to 7.0 m above the water level. The perched floodplain was located irregularly along the river, with a higher portion between the Podbánske and Pribylina, and around the small hydraulic power station near Dovalovo. In some places, three levels of the river floodplains (Fig. 8) along the Belá River were identified, with limited or no active floodplain. The first location was identified in the Tichý and Kôprovský creek confluence, and the other location was located around the small hydraulic power plant near Vavrišovo (Fig. 1).

The active river floodplain represents 3.635 km^2, 38.8% of the topographic floodplain (including island area 0.374 km^2). The height of the active floodplain was considerably lower, from – 1.0 m to 2.5 m. The active floodplain or potentially active floodplain was extended mainly from Podbánské downstream to the small hydroelectric power station near Vavrišovo. The largest extent was situated in the vicinity of the Pribylina. The width of the river floodplain increased along the whole Belá River, with the most extensive around Liptovský Hrádok (Fig. 5 and Fig. 6). However, the width of the active floodplain was reduced in this part by the dike constructions in the middle of the 20th century.

4.3 Spatial Statistic

Altogether, 2,177 polygons of the newly formed floodplain were generated, by the overlapping of river channel position of aerial images from 1949 to 2018, representing 1.252 km^2. In total, the most extensive floodplain was formed from 1949 to 1986 (Fig. 9). However, the periods were not equally long, and the increase per year fluctuated. The mean formation of floodplain per year was 31,228 m^2. The increase in floodplain that occurred between 2003–2006 almost the doubled mean formation of floodplain per year. The mean relative elevation value of the formed floodplain was decreasing gradually. While the floodplain

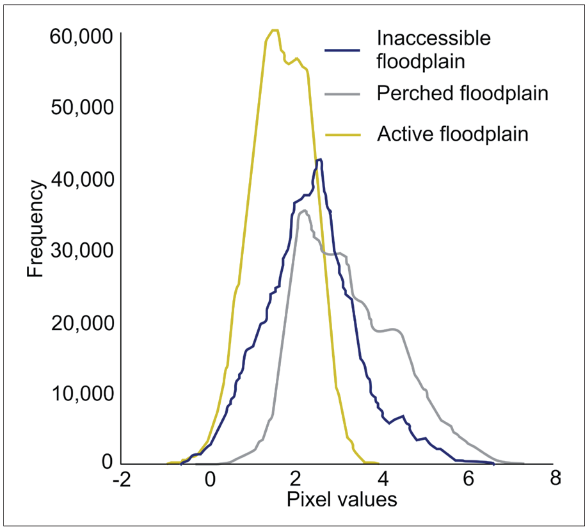

Fig. 7: Three floodplain pixel values distribution based on REMwater^{GPS}
Source: Authors' elaboration

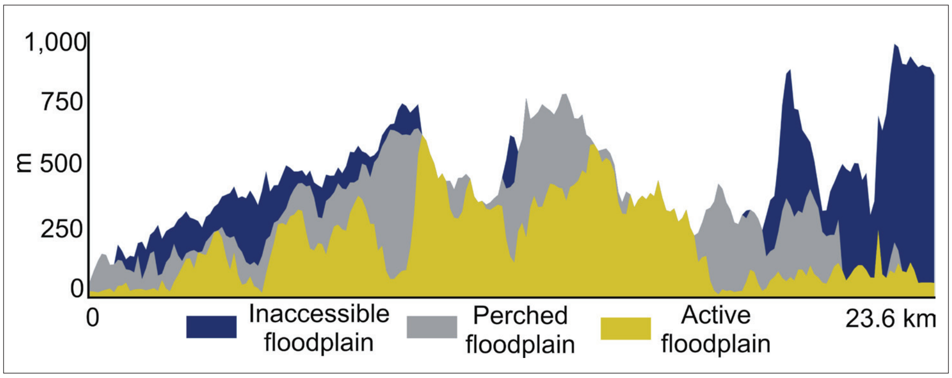

Fig. 6: The floodplain width variation measured every 100 m
Source: Authors' elaboration

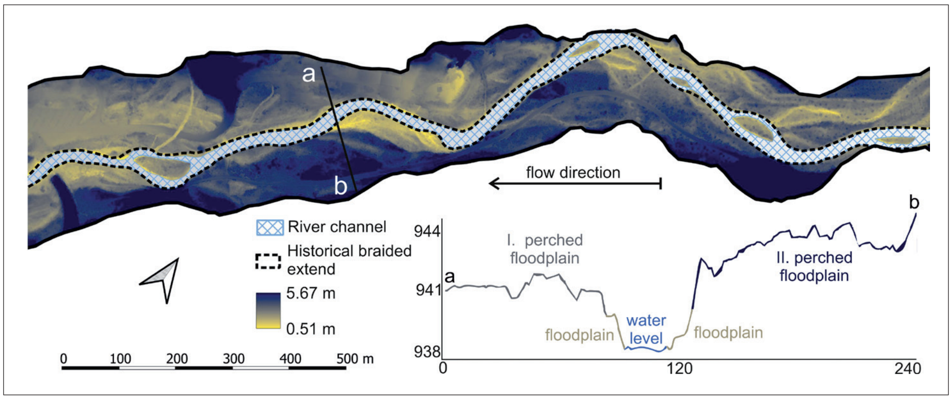

Fig. 8: The highest part of the Belá River floodplain is not fully developed, but there are still remnants of the former position of the channel and perched floodplain formation, marked as I. and II. perched floodplain
Source: Authors' conceptualization

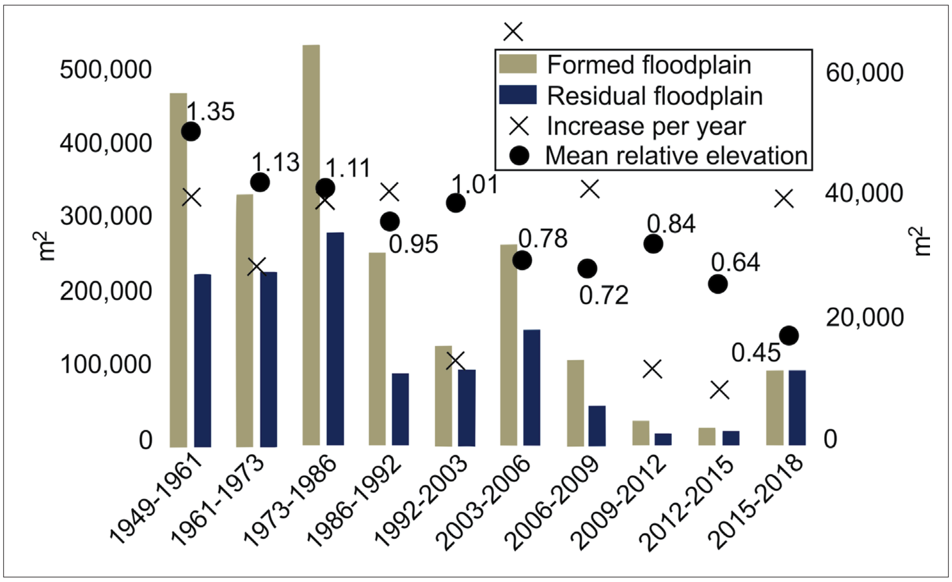

Fig. 9: The graph visualizes the increase of floodplain formation based on aerial photography and a present remnant of the formed floodplain (scale on the left), the increase of floodplain formation per year (scale on the right) and the present relative elevation of the floodplain derived from REMwater^{GPS}
Source: Authors' calculations and elaboration

formed between 1949 to 1961 has a relative height of 1.35 m, the floodplain formed from 2015 to 2018 has a relative height of 0.45m. The older parts of the river floodplain were situated higher compared to a recently formed floodplain, indicating the gradual incision of the water stream.

The spatial statistics was used for identification of the processes of the recent floodplain formation, for the three REMs. Based on the 'Spatial Autocorrelation (Morans I)', large values in z-score and extremely low p-values were received, indicating statistically significant hot spots and statistically significant cold spots of the floodplain formation from 1949 to 2018. Based on that, the null hypothesis was rejected in each case (Tab. 3) of the statistic, and also Moran's Index pointed to a clustered pattern of polygons in each case. The processes in the river have a trend of developing a new floodplain either by incision of the river channel or by simplifying the original braided river pattern.

The river floodplain was formed irregularly along the Belá River, while two processes predominated, incision and simplification. The locations of the processes were identified by hot spot analysis, complemented by cluster analyses and visualized for a better spatial interpretation (Fig. 10). None of the mentioned processes prevailed, but they occurred evenly along the stream. In the upper part of the river, near the confluence of Tichý Creek and Kôprovský Creek, the river floodplain was perched, narrow, and poorly formed. Most of the river floodplain was relatively high concerning the river channel. Moreover, the active and newly formed river floodplain were made up of isolated floodplain pockets, accompanied by incision. There was no space for the channel shifting and the new floodplain was created sporadically by the sediment accumulation.

More significant river floodplain formation occurred between the Podbánske and Pribylina settlements. The incision of the river channel was caused by the abandonment of the side channels, which became part of the floodplain. The greater shifting of the river channel was limited mainly by its confinement by the left-hand terrace which cut bluffs, and the perched floodplain along both sides of the Belá River in the higher part of the river. In the section with cut bluffs of the terrace, the active floodplain has the same width as a topographic floodplain.

In the vicinity of Pribylina, the river floodplain was significantly developed as a result of river training. The lateral, right-side channels were artificially cut off from the rest of the braidplain and thus became part of the river floodplain. However, these may become active again in the event of high-water levels or erosion of the artificial gravel embankment. The hot spot analysis shows these abandoned channels as cold spots, but the cluster analysis identified higher elevation portions of the river floodplain on the opposite side with no river training.

These portions of the floodplain were statistically less significant, but the trend of higher values continues and culminates approximately one kilometer downstream, below the village of Pribylina. Between Pribylina and Vavrišovo, a river floodplain developed mainly by simplification of the braidplain, confirmed by cold spots and low values of the clusters (Fig. 10). In this part of the stream, the active floodplain extended to the entire width of the topographic floodplain, and the Belá River is potentially able to migrate in the whole width.

A significant change occurred near the village of Vavrišovo, where the small hydroelectric power plant was built. As a result, the river channel was significantly simplified and simultaneously incised. The original part of the river floodplain was several meters above the current watercourse and the river floodplain was completely cut off from the watercourse. The incision reached more than 5 meters and several stages of development of the river floodplain can be identified. These stages thus became a perched floodplain, active 70 years ago. The perched floodplain

REM type	Moran's Index	z-score	p-value	Pattern	Null hypothesis
REMwater^{DTM}	0.507134	170.652381	< 0.00000	clustered	rejected
REMwater^{GPS}	0.466663	154.835203	< 0.00000	clustered	rejected
REMbottom^{GPS}	0.447573	148.506958	< 0.00000	clustered	rejected

Tab. 3: The result of the "Spatial Autocorrelation (Moran's I)" analysis for three REMs
Source: Authors' calculations

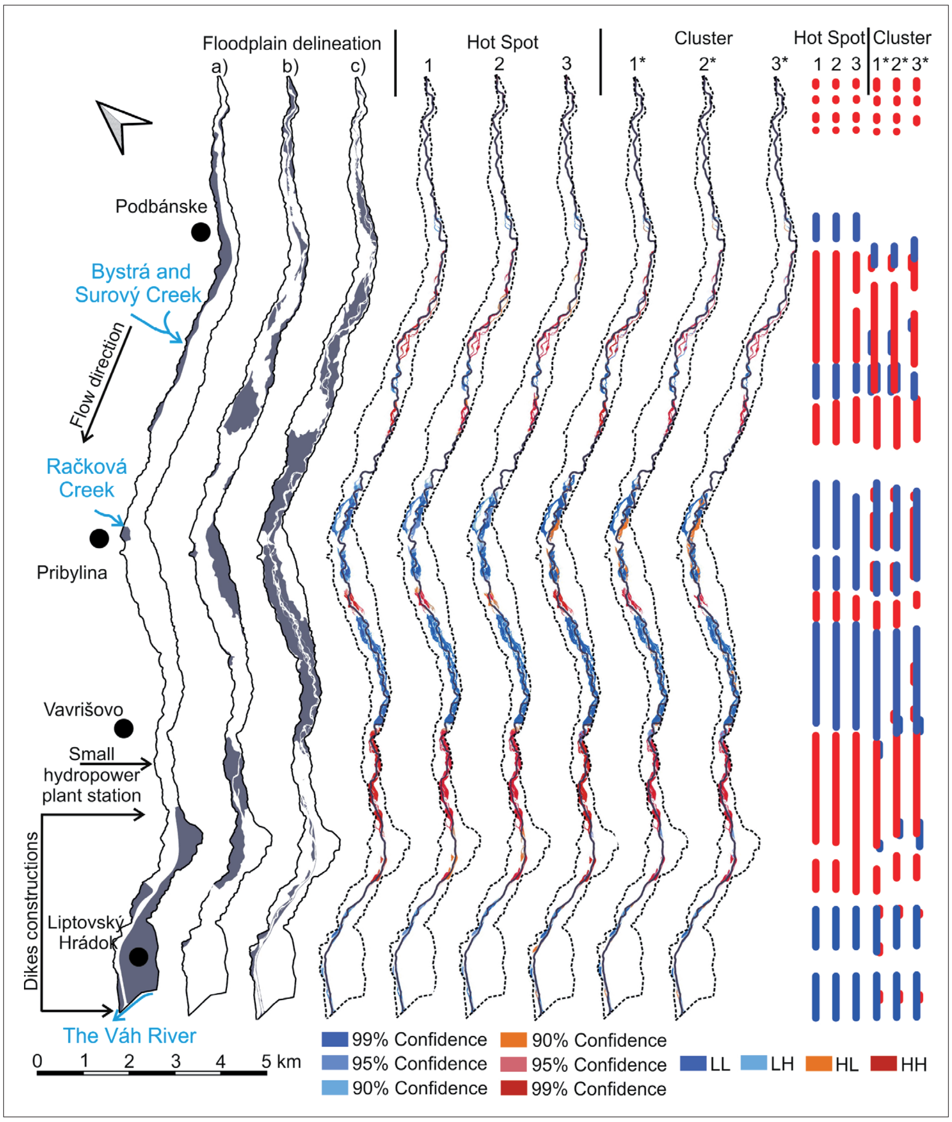

Fig. 10: On the left side, maps represent three types of floodplain delineation based on REMs models: a) inaccessible floodplain, b) perched floodplain, and c) active floodplain. For every REM the "hot spot analysis" and the "cluster and outlier analysis" were run for new floodplain formation from 1949 to 2018. Altogether, three REMs were used, REMwater^{DTM} (1), REMwater^{GPS} (2), and REMbottom^{GPS} (3). On the left, the results of analyses are visualized by maps. The cold spot Confidence is visualized in blue colour and hot spot confidence in red colouration. The cluster of low values (LL) and low values surrounded primarily by high values (LH) have blue colouration, and high values (HH) and high values surrounded primarily by low values (HL) have red colouration. The cross sections on the right represent 150 m long sections of the floodplain and river channel typical for each part of the river floodplain
Source: Authors' elaboration

stretched from the Vavrišovo to the Liptovský Hrádok, where in the middle of the last century the watercourse was significantly modified by the construction of dikes. In this lower part of the stream, the floodplain was situated only as a floodplain pocket or is completely lacking, and the river channel occupied the entire space between the dikes. The formation of the new river floodplain was insignificant and only in small patches, which shows cold spots in the spatial statistics. Paradoxically, the part of the stream with the widest topographic floodplain lacks an active floodplain completely.

5. Discussion

5.1 The REM generation

The river floodplain along the Belá River was formed into an active and perched river floodplain by discharge changes and anthropogenic interventions. The complex topography of the floodplain, its significant changes in gradient and height prevented floodplain level identification from DTM (Fig. 4) or orthophoto images. Therefore, three REMs were created that adjust and normalized the river floodplain elevation according to changes in the river channel elevation.

The REMs indicated a noticeable similarity in value distribution (Fig. 5). The distribution of the values was not uniform, and the histograms demonstrate the sharp redistribution changes, for example around 5 m above the channel (Fig. 5). Despite this, there were found no connection between these value distributions and the further floodplain level delineation. Previously, the models were used in basic floodplain visualization (Coe, 2016), in the identification of side channels (Jones, 2006) and riparian vegetation (Dilts et al., 2010; Slaughter & Hubert, 2014), or in the delineation of migration zone of a river (Olson, 2014). However, there was no research focused on floodplain delimitation or floodplain process-oriented model of floodplain development.

The quality and success of the model depended on the type of input data. While Jones (2006) used an actual water level derived from the LiDAR point cloud, Dilts et al. (2010) used an inundation level, and Greco et al.(2008) used a dry season base-flow channel water surface. There was no recommendation or required type of input. The water level naturally fluctuates, and the bottom is formed by riffles and pools. The bank-full condition seems to be the most appropriate for the identification and analysis of fluvial features above the river channel. However, determination of the bank-full condition for a lowland stream is easier as opposed to a braided stream, where high gradient and sinuosity of the channel could be a problem for the model (Coe, 2016). The incision of the Belá River, a large accumulation of material on the banks, and the dynamic nature of the water stream disenables acquiring the required data. Therefore, three types of data were used and compared, including channel bottom elevation.

The research focusing on model building from the bottom of the channel has been lacking. Greco et al. (2008) used the channel bathymetry as information for average summer low-flow value, but not as a reference elevation. In the research, water level data and bottom elevation data were collected by GPS. Their comparison did not show significant differences in the patterns and distributions of values. Anyway, the result depends not only on the quality of the data but also on the experience of the data collector. Additionally, if the REMwater^{DTM} and REMwater^{GPS} are compared, only small differences are distinguishable. Yet, it is possible to collect data by GPS in one terrain survey with no huge water level fluctuation, while accessible LiDAR data can often be collected in the span of a few days with different water levels.

The water level values have been interpolated from points (Olsen et al., 2014) and cross-sections (Jones, 2006). Dilts et al. (2010) pointed out that the method of the parallel cross-sections and perpendicular cross-sections on the river channel (Fig. 11a and 11b) distribute values irregularly. The point interpolation was inappropriate for the high sinuous Belá River, where the lower parts of the sinuous channel could disproportionately affect the lower or higher portion of the floodplain. Besides, the interpolation accuracy decreased with increasing distance from the Belá River, and the REM values should be the most accurate close to the main river channel (Greco et al, 2008). The modified cross-section method was used in this study as the most appropriate method with the best results. The cross sections were placed perpendicularly on the centre line of the floodplain (Fig. 11c) every 500 m, along the centre line of the floodplain. This ensured that even the furthest points on the floodplain reach the same relative height accuracy as the nearer locations perpendicular to the river channel, in comparison to other methods. Additionally, a very dense distribution of cross-sections created too sharp and disturbing a transition of REM (Fig. 12). High stream gradients and step-pool morphology indicate more frequent knickzones occurrence (Hayakawa & Oguchi, 2006), which could affect the final model.

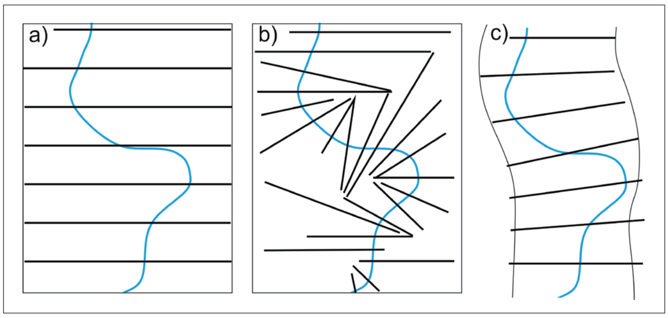

Fig. 11: The methods of cross-section settings. The a) represent parallel cross sections, which do not respect the sinuous of the river, b) represent cross sections perpendicularly on the river channel, which leave large gaps and the interpolation could inappropriately affect the different parts of the floodplain. Compromise is the method c), where the cross-section lines are leading perpendicularly on the floodplain centre line
Source: Authors' conceptualization based on Dilts et al. (2010)

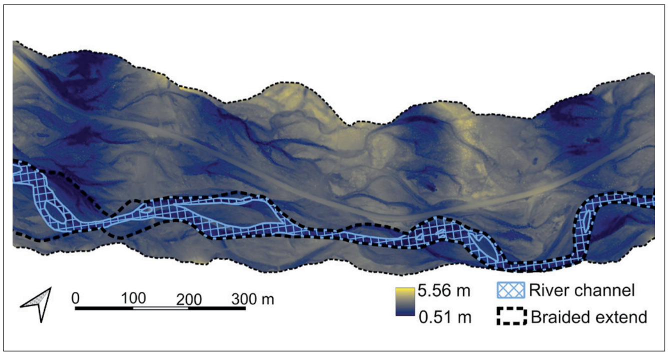

Fig. 12: The REM model was generated from the water level by a 100 m cross-section. Too dense cross sections created irregular model due to channel gradient changes. A similar problem appears with DTM detrended for channel gradient
Source: Authors' conceptualization

5.2 Floodplain delineation

The extension and identification of a river floodplain could differ depending on the determination of the principles of its delimitation (Křížek et al., 2006). Different approaches on how to delimit floodplains were presented by Lóczy et al. (2012), together with the identification of four subdivisions of the river floodplain based on slope, floodplain width, sinusoid, valley confinement and maximum relief. The floodplain along the Belá River was delimited by the edges of the terraces. The different transitions in the river stream affected the character of the floodplain (Jain et al., 2008). During the development and formation of the floodplain along the Belá River, levels of floodplain were created, separated by different heights and in some places formed to a perched floodplain identified based on the REMs.

A high and low floodplain was identified by Kiss et al. (2017) by cross sections, but REMs provided a proper method of identification of perched floodplain on an extensive spatial scale. However, there was no exact elevation value that separates the floodplain levels. They were identified due to sharp edges and higher continuous surfaces on REM (Fig. 4), significantly separated from the river channel. Eder et al. (2022), identify former floodplain, active and potential floodplain along the Danube River based on the inundated areas and historical data. On the other hand, the REM allows the possibility of identifying multiple levels of floodplains, their edges and also forms located around the watercourse, such as ledges, dikes or other artificial structures.

Additionally, the REM could have broad utilization in design tools for planting plans in riparian restoration projects or for predicting the presence of plant communities (Greco et al, 2008). Figure 13 shows the relative elevation of settlements and buildings concerning the REMs. The settlements Liptovský Hrádok or Pribylina spread on the floodplain relatively low to the river, protected by dikes and the recreational facilities spread relatively high to the river. On the other hand, the marginalized Roma community, situated only tens of meters away from the braidplain of the Belá River is situated on a relatively low floodplain unprotected by dikes (Fig. 13). This could be an example of using the REM in environmental justice or flood hazard analysis. Besides that, the REM could be valuable information for estimating and predicting flood inundation patterns or surrogate water table model (Greco et al., 2008), or it is possible to look for a correlation between the height of the floodplain and vegetation quality due to incision of the channel.

5.3 The floodplain formation

The river floodplain widened and narrowed unevenly downstream. In the uppermost part at the confluence of Tichý and Kôprovský Creeks, the topographic floodplain was the narrowest

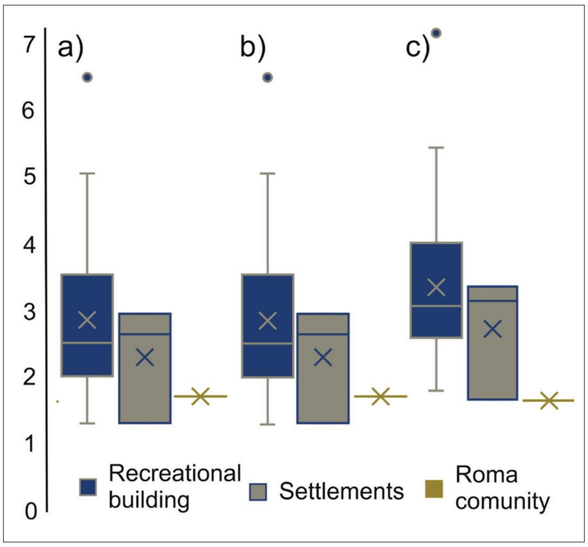

Fig. 13: The box plot presents the distribution of mean values of relative height to the water level for three types of settlements. The mean values were generated from: a) REMwater^{DTM}; b) REMwater^{GPS}; c) REMbottom^{GPS}. The recreational buildings are scattered at the floodplain without dike constructions. The settlements (Liptovský Hrádok and Pribylina) are situated behind the dikes. The marginalized Roma settlement is located close to the river without flood protection
Source: Authors' conceptualization

with an almost absent active floodplain. The channel had a single-thread character (Lehotský et al., 2018) and with floodplain pockets resemble a canyon character, which had specific conditions for the development of the floodplain (Tranmer et al., 2015). There was a significant change in the height of the river floodplain, where two floodplain levels were identified, the upper exceeding 3 m (Fig. 8). Spatial statistics shows the formation of floodplain in the area in patches, with high relative elevation.

The higher part of the floodplain could be considered a low terrace because of the missing interaction with the channel, with many recreational facilities exhibited in this section. It seems, that the higher parts of the river floodplain are more stable. Haschenburger and Cowie (2009) term stable parts of floodplain along the braided river as a mature floodplain and suggest that by dating it is possible to shed light on when conditions change which led to the formation of stable parts of the floodplain.

Gradually, from Podbásnke to Vavrišovo, an expansion of the topographic river floodplain appeared. The expansion of the floodplain in the foothills area was observed similarly by Lóczy et al. (2012). The active floodplain along the Belá River was significantly narrowed by the road embankment between Podbánske and Pribylina, and by the perched floodplain along both sides of the channel almost in the whole river reach. A noticeably extended perched floodplains and contraction of active floodplain was formed by the channel incision after the Surový and Bystrá Creeks flow to the Belá River. The incision since 1949 is highlighted by spatial statistics (Fig. 10).

The side tributaries could have a strong influence on the river reaches, and disturb them (Nardi & Rinaldi, 2015). The difference in the amount of precipitation and the amount of sediment input in a sub-basin can strongly influence the local formation of the floodplain. For example, a decreasing discharge has been observed since mid-20th century with no flood situation exceeding a 10-year recurrence interval since 1958 to 2018 (Fig. 2). Catastrophic flood events have also been absent since 1958. Furthermore, the right-sided channel of Belá River before Račková Creek confluence, was narrowed and shifted closer to the main channel between 1949 and 1961, probably as a result of the lack of flood events. More importantly, the relative height of the channel decreased in average only slightly from 0.29 m to – 0.3 m. In 1973 the channel was inactive. This leads us to the idea, that the river floodplain could be formed by gradual incision of the main channel, and simultaneously by narrowing and simplification of the braidplain. Abandoning of side channels caused by vast incision which reached from 3 to 5 m has been observed on the Prahova River (Armaş et al., 2013). On the Belá River, such vast incision could be mitigated by local cut-bluffs sediment input.

The river channel before Pribylina is confined to the left-hand terrace, causing multiple cut-bluffs. Only in one cut-bluff 10,102.9 m^3 of mass was transferred to the river (Rusnák et al., 2020). It can be assumed that the amount of sediment supplied to the channel during the cut-bluffs could mitigate the incision of the stream. Along and downstream of the cut-bluffs, the simplification of the river channel and the formation of a river floodplain was observed, without channel incision. Moreover, from the vicinity of cut-bluffs downstream, the perched floodplain was replaced by the active floodplain across its entire topographic floodplain width. The amount of material that entered the river probably affected the floodplain formation and prevented extensive cutting of the channel.

According to Lehotský et al. (2018), the whole Belá River showed a simplification process due to sediment transport interruption. The narrowing and simplification of the channel with no or very limited incision, resulted in the formation of an extensive river floodplain between Pribilina and Vavrišovo (Fig. 10). According to Majerčáková et al. (2007), decreasing discharges together with a lack of extreme flood events and a change in the sediment supply (Kidová et al., 2016a) negatively affected the channel pattern from braided to single-thread channel (Kidová et al., 2016b). Dufour et al. (2015) claimed that the narrowing and transformation from the bar-braided river pattern to a single-thread system that occurred on the Magra River was a result of local factors rather than long-term. Nevertheless, the transformation of the Belá River seems to be rather a regional problem (Wyżga et al., 2016) than a local one.

Generally, braided rivers are formed by the pulse character of flood events (Bertoldi et al., 2010) and are sensitive to floods (Nardi & Rinaldi, 2015). If the pulses are missing, the channel pattern is simplified (Kidová et al., 2016a). This can affect riparian plant species since many species depend on the reshaping of the braidplain (Tockner et al, 2000). The missing flows and extreme flood events (Fig. 2) led to the narrowing and simplification of the braided river pattern of the Belá River (Kidová, 2016a) and consequently to a new river floodplain formation. However, the incision of the riverbed was observed only locally. The reduced peak range created a larger and relatively stable area in the Ngaruroro River in New Zealand, where degradation of the braided river pattern did not necessarily lead to significant channel incision (Haschenburger & Cowie, 2009). The increase of floodplain formation was observed also in the Polish Carpathians accompanied by expansion of the riparian forests (Hajdukiewicz & Wyżga, 2022). The trend of degradation and simplification of river channel patterns of mountain and submountain streams is a far-reaching issue, not a regional problem.

However, floodplain formation can be disrupted by strong anthropogenic impact. The river floodplain around the Vavrišovo had a canyon character stronger than the upper most part of the river but with a lower gradient. The canyon character was a result of the construction of a small hydroelectric power plant. The stream was significantly incised and the lateral connectivity between the channel and the floodplain was interrupted (Kidová & Lehotský, 2013). Rusnák et al. (2018) detected the advancing incision in the locality by UAV by identification of three bar levels. Additionally, the incision supported sliding activation upstream (Rusnák et al. 2020).

The active floodplain in the locality of the small hydroelectric power plant was absent totally, surrounded by the perched floodplain, with relative elevation reaching up to 5 m from the channel bottom. The spatial statistics supported the previous observations and research and displayed the extent of the perched floodplain in the area. Besides, the perched floodplain represents the former active braidplain in the mid-20th century. Haschenburger and Cowie (2009) suggested that aggradation and also degradation may promote floodplain formation. However, the degradation of the Belá River due to anthropogenic impact is so extensive that it promotes direct perched floodplain formation. On the other hand, the process of incision of the river channel can trigger its widening, by exceeding a critical height for mass failure of channel banks (Bollati et al., 2014).

Downstream the topographical floodplain reaches a width up to 1 km, largely replaced by isolated inaccessible floodplain behind the dike constructions. The dike constrictions interrupt the connectivity between the channel and the floodplain (Kidová, 2010), accompanied by gravel mining as an additional human impact affecting the channel (Radecki-Pawlik et al., 2019). The channel bed was reinforced by a stabilization threshold to prevent additional incision in the river reach (Kidová, 2010). In the locations where the dikes were not constructed, the perched floodplain was formed. Due to the limitation of the active width of the river, floodplain development becomes less likely (Haschenburger & Cowie, 2009). The effect of the anthropogenic impact was an obvious interruption of the lateral connection of the channel with the rest of the floodplain. Furthermore, the active river floodplain between the dikes further from the small hydroelectric plant exhibits a gradual decrease of hot spot and their replacement by cold spots within the spatial statistics.

The impact of the small hydropower plant decreased gradually downstream demonstrating its negative impact and the disruption of the lateral connectivity of the Belá River (Lehotský et al., 2018) since its construction (Kidová et al., 2016a). In the Polish Carpathians rivers, the channel width decreased to 21–65% of the value from the 1870s since 2009 (Hajdukiewicz & Wyżga, 2022) due to anthropogenic impact. Using the example of the Belá River, the changes in discharges and sediment supply changes have prompted a simplification of the river pattern, but not necessarily the incision of the channel into the bedrock, primarily induced by anthropogenic interventions in the stream. Nowadays it is possible to demonstrate the different impacts of climate change and anthropogenic impact. However, according to Majerčáková et al. (2007), if the catchment has too many local anthropogenic impacts in the future, the parsing of total impact into anthropogenic impact and climate change impact will be essentially impossible.

The floodplain along the Belá was developed predominantly by narrowing and incision of the main channel. It is evident that incision is quite active near the tributaries or the anthropogenic impact section, while simplification is the main process along the whole water stream. In the presented research, the perched floodplain has been identified from REMs and in the vicinity of the small hydropower plant station, after the confluence of the Kôprovský and Tichý Creeks and after the confluence of the right-sided tributaries with the Belá River, while the active floodplain followed. The ongoing processes have been confirmed by spatial statistics.

While Bollati et al. (2014) claimed that there was no reliable determination of whether incision and narrowing started simultaneously or if one of the two processes supported the other, this research suggests that the simplification was accompanied by incision, advancing contraction of the braidplain and gradual lowering of the riverbed (Fig. 9). These processes were intensified in locations with side tributaries, and by anthropogenic intervention, which strongly and significantly influenced erosion-accumulation processes in the river reaches. Primarily the anthropogenic impact can initiate considerable incision of the riverbed (Ziliani & Surian, 2012).

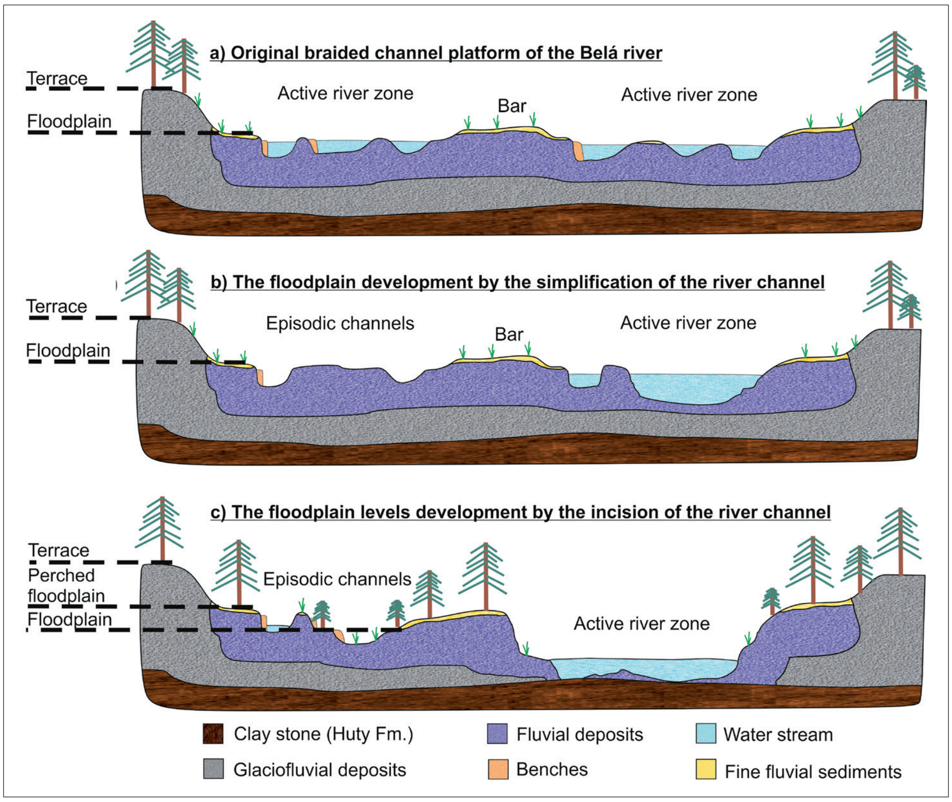

Fig. 14: The sketch represents a basic concept of the process model. The original braidplain is followed by two ongoing processes on the Belá River, responsible for river transformation and floodplain development
Source: Authors' conceptualization

The results lead us to the idea, that the perched floodplain could be considered a result of cyclical channel evolution, which is typically characterized by an initial degradation (phase of initial bed incision), resulting in bank unstability and widening, and finally completed by a stage of aggradation (Bollati et al., 2014). The perched floodplain was identified along the Belá River as a presumable remnant of the completed cycle of channel evolution. Dating of the perched river floodplain could determine when a similar cycle occurred. The recent evolution of the Belá River indicates the predominant initial phase of the cycle in a major part of the river, based on gradual simplification and abandoning of the side channels. It can be presumed, that the contemporary simplification and incision of the river will develop an additional level of the perched floodplain made of the current active floodplain.

6. Conclusions

The submountain Belá River can be understood as a glacial relic, which is more susceptible to climate changes and anthropogenic interventions. Decreasing discharges, lack of extreme flood events, modification of land use in the catchment area and anthropogenic interventions have affected the Belá River over the last 70 years, resulting in the simplification of the river pattern (Kidová et al., 2016b). Moreover, the anthropogenic interventions have intensified the ongoing processes. Using the Relative Elevation Models (REMs), it is possible to identify the active, inaccessible, and perched floodplain with its levels. In combination with floodplain dating and spatial statistics, two basic evolutionary processes in progress have been identified (Fig. 14) affecting the river floodplain development:

a. The original braided channel planform is characterized by numerous active channels, separated by gravel bars. The river floodplain is formed along the edges of the active river zone by shifting and repeated contraction of the braid plain. However, human intervention, discharges decreased and increased forest cover affect the channel planform and initiate the two main processes of river transformation and floodplain formation.

b. The first process which transforms the river and forms the floodplain is the contraction of the braidplain. As a result of simplification and narrowing of the active river zone, the new floodplain develops along the river sides. The gradual formation of one dominant channel, and the river floodplain prevails. During increased discharges and catastrophic floods, the braided pattern can be restored. In addition, the river floodplain still fulfils the function of accumulating and mitigating floods.

c. The second process is the development of single-thread channel with a strong incision that causes an interruption in the lateral connectivity of the river channel with the surrounding floodplain. The river floodplain forms into several levels and creates a perched floodplain. The reformation of a floodplain is absent due to the impossibility of river channel migration. In case of increased flows and catastrophic floods, there is no connection between the river and perched floodplain levels. The river floodplain no longer has the function of accumulation and mitigation of floods, which can lead to increased floods in the lower parts of the Belá River.

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Data availability

The data used in the research were obtained from: ÚGKK SR, including LiDAR data and aerial photos available at: https://www.skgeodesy.sk/sk; geological maps available at: https://www.geology.sk/geoinfoportal/mapovy-portal/geologicke-mapy/; and data from Slovak hydrometeorological institute (SHMÚ).

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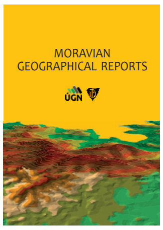

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Analysis of spatio-temporal development of mining landforms using aerial photographs: Case study from the Ostrava–Karviná mining district

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Abstract

The anthropogenic relief transformations of the mining landscape are characterised by high dynamics of changes over time that can be effectively mapped on a large scale using aerial images. The Karviná part of the Ostrava-Karviná mining district, which stands for significant hard coal mining area in the Czech Republic, has been selected to analyse the spatio-temporal development of anthropogenic landforms. Anthropogenic landforms were visually identified from the aerial images from 1947, 1966, 1971, 1985, 1994, 2009, and 2018. Specific anthropogenic landforms were analysed along with their spatio-temporal changes based on obtained vector data. The total extent and number of anthropogenic landforms increased the most during the periods 1947–1966 and 1971–1985. The same anthropogenic landforms occurred on circa 24 hectares in the entire period 1947–2018. The most anthropogenic landforms remained preserved in the last observed period 2009–2018. The multi-temporal analysis of aerial photographs and overlay operations in GIS enabled to map the age of specific landforms and to identify changed or unchanged anthropogenic landforms. This method is suitable for the study of landform dynamics at mining sites and is particularly relevant for the planning challenges in post-mining reclamation.

Keywords: *Mining landforms, aerial image, visual image interpretation, spatio-temporal changes, landforms age, Ostrava–Karviná mining district*

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1. Introduction

Landscape affected by underground hard coal mining belongs to areas with highly dynamic landscape changes. Increasing mining intensity brings dynamics into anthropogenic transformations of landforms accompanied by changes in other landscape components. Underground hard coal extraction thus has a cumulative impact on the landscape components (Lei et al., 2009). Underground hard coal mining in the landscape is primarily reflected in anthropogenic landforms. In addition to the formation of mining landforms, it can also result in planation (Dávid, 2008). This involves the use of dump material to fill in ground subsidence, for example.

In the study of a dynamically changing landscape, remote sensing data represent a significant non-generalised source of information on the state of the Earth's surface in a given moment. The spatio-temporal changes of various properties and phenomena in the landscape can also be studied more easily thanks to the higher temporal resolution of images as compared to other types of spatial data. These characteristics predetermine the use of archival aerial images in the mapping and analysis of the spatio-temporal development of anthropogenic landforms on a large scale. Moreover, in comparison with satellite images, another benefit of aerial images is a longer time period that the images cover. They can be applied in the analysis of landscape changes in areas of mineral extraction (Lausch & Herzog, 2002; Popelková & Mulková, 2018; Santo & Sánchez, 2002) and in studies focusing on mining landscape reclamation (Sklenička & Lhota, 2002).

With regard to aerial image properties and the purpose of their use in our study, visual interpretation of aerial image time series is a suitable tool to monitor the spatio-temporal changes of mining landforms, thanks to which the landforms may be inventoried and subsequently analysed their development using GIS. GIS tools can be used for mining landscape analysis even in the case of land use change assessment in relation to landforms (Ikemi, 2017). Although our study is primarily focused on the mapping of anthropogenic landforms in mining landscape, the chosen methodology will find wider application in research on the development of other Earth's surface landforms. Thus, the chosen combination of visual photointerpretation of historical aerial photographs and GIS tools can be used to monitor various long-term and short-term changes in the landscape without limitation to the Central Europe region.

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To validate the methodology, we analyse the development of mining landforms in the Karviná part of the Ostrava-Karviná Mining District (OKMD), an important area of underground hard coal mining in the Czech Republic.

The landforms and landscape structure is significantly transformed by mining anthropogenic landforms. These forms may persist in the landscape for short or long periods of time. In our study, we focused on the mapping of anthropogenic landforms from multi-temporal aerial photographs. In addition, we focused on analysing spatio-temporal changes of the landforms specifically in the period 1947–2018. Analysing spatio-temporal changes of the mining anthropogenic landforms is important both in terms of methodological advancement and its relevance for reclamation planning in mining sites. In this respect, it shows the potential and advantages of using historical aerial photographs for mapping mining landforms even in the past and for determining the age of landforms.

Our study deals with the influence of human activities on the landscape in an important area of underground hard coal mining in the Czech Republic. The following goals were set: (1) mapping the occurrence of anthropogenic landforms in the hard coal mining district in the period of 1947–2018; (2) assessing mining landforms in all years under consideration; (3) analysing spatio-temporal changes of anthropogenic landforms.

2. Theoretical background

First studies dealing with the research of anthropogenic landform changes in the Ostrava-Karviná mining district focused on convex anthropogenic landforms (Kroutilík, 1954) and since the late 1950s on the issue of tailings reclamation (Drlík, 1960, 1964; Havrlant et al., 1967; Gerlich, 1973 in Havrlant, 1980). The first scientific works focused on anthropogenic landforms in the OKMD thus arose out of the need for landscaping (Popelka, 2013). From the late 1960s onwards, Miroslav Havrlant conducted biogeographical research on the OKMD waste dumps (Havrlant, 1967), and in the late 1970s he carried out a thorough inventory of the condition and form of the dumps (Havrlant, 1980). Miroslav Havrlant mapped anthropogenic areas affected by mining extraction in the OKMD at a scale of 1:25,000 and 1:50,000. Anthropogenic landform changes in the Karviná part of the Ostrava-Karviná district were mapped by Jan Havrlant (1997a, 1997b, 1999). The author states that waste was deposited on 11 large central waste dumps, while in the 1990s most of the waste was used for reclamation purposes and was not purposefully deposited on new dumps. There were also 45 tailings ponds within the area. The size of subsidence reached up to 30 m in Karviná-Doly. The flooded area occupied 13% of the total area affected by subsidence. Other scientific projects dealt with the assessment of the state of mining landscape and options of landscape restoration (Raclavský, 2004; Stalmachová, 2004).

The Institute of Geonics of the Czech Academy of Sciences solved the issues of the decline in hard coal mining and its effect on the landscape of the Ostrava region (Martinec et al., 2003; Mikulík et al., 2004). An atlas of maps on a scale of 1:50,000 was created as a part of the project. The atlas includes maps of the impact of undermining with subsidence in the period 1961–1999, which were prepared on the basis of calculated subsidence. In some places they were compared with the actual measured values. In the Karviná part of the OKMD, 20 waste dumps and 24 tailings ponds were mapped with the state of the reclamation process indicated (Martinec et al., 2003). Mikulík et al. (2004) classified anthropogenic landforms into three main groups: convex forms, concave forms and silt fields. Within the whole OKMD, he recorded 46 waste dumps and 96 tailings pools. Martinec et al. (2006) distinguished 5 stages of development of waste dumps from fresh waste rock without atmospheric and biological effect, through two different stages of oxidation of waste dumps, to the afterburning of waste and the formation of bourn-out waste heaps. The size of subsidence in the Karviná region was estimated to be up to 40 m in places. Within the framework of this project, a map of anthropogenic landforms of the Ostrava region was prepared at a scale of 1:50,000 showing the situation as of 1988 (Mikulík et al., 2004). Zástěrová et al. (2015) focused on defining the natural conditions of waste dumps.

The knowledge of the local geological, geomorphological and hydrogeological properties of waste dumps is considered important in dealing with old burdens from mining activities. Kadlečík et al. (2015) focused on determining the extent of ground subsidence in the Karviná part of the OKMD in the Louky mining area using Differential Interferometry SAR (DInSAR) in comparison with GPS monitoring. DInSAR allows monitoring spatio-temporal changes in ground subsidence. If this method is used, it is necessary to know the extent of underground mining and changes in anthropogenic landforms. The monitoring of the development of subsidence depression using GPS methods in the Louky mining area in 2006–2010 was carried out by Doležalová et al. (2009) and Doležalová et al. (2012). The size of subsidence of the measured points ranged from less than 0.6 m to 1.7 m. Research on long-term changes in the use of the OKMD landscape in the 19^{th} and 20^{th} centuries was reported by Popelka et al. (2016). Mining landforms are also analysed in hard coal mining areas of neighbouring states, for example, the Ruhr District in Germany (Harnischmacher, 2007), the Upper Silesian coal mining region in southern Poland (Dulias, 2016, Szypula, 2020), and Walbrzych city in SW Poland (Jancewicz et al., 2020). Szypula (2013) statistically analysed anthropogenic line forms in the southern part of the Silesian Upland.

Statistical data and maps, including archival data, were used to investigate the impact of coal mining on the landscape of the Upper Silesian Coal Basin in Poland. Based on the input data, digital elevation models and morphometric databases were created and indicators of anthropogenic denudation were calculated (Dulias, 2016). Field research was also conducted to map contemporary geomorphological processes within selected anthropogenic landforms. In the Upper Silesian Coal Basin, direct anthropogenic landforms are found over an area of almost 150 km^2, with concave landforms outweighing convex landforms. Sandpits play the most important role, being found on more than half of the area of all post-mining landforms (Dulias, 2016). In 1993, there were 302 waste dumps in the area, covering an area of 49.2 km^2. The older ones are conical in shape. Many of the waste dumps are in the shape of massive mesas or have an irregular shape with several culminations. The largest subsidence occurred in the period 1960–1980 in connection with very intensive coal mining. Until 1991, maximum subsidence in the range of 24–28 m was recorded in Ruda Ślaska (Dulias, 2016). During coal mining in the Ruhr District since the early 19^{th} century, various mining landforms were created. The most important of them are waste dumps and mining subsidence (Harnischmacher, 2007). The earliest waste dumps were conical in shape, which later changed to an irregular or tabular (plate-like) shape. The size of subsidence ranges from a few metres to 20 m with a maximum recorded subsidence of 24 m. Modelling of subsidence in the central part of the Walbrzych (Poland) coal mine in geographic information systems with geographically weighted regression (GWR) method was also addressed by Blachowski (2016).

Geoinformation technologies that use a wide range of input data (e.g. maps, remote sensing data, DTM) extend the possibilities of the mapping of not only mining anthropogenic landforms. Ursu et al. (2011) used maps and aerial and satellite imagery to map anthropogenic landforms. The anthropogenic landforms were analysed using GIS software and subsequently a map of different types of anthropogenic influence on landforms was created. The anthropogenic landforms were also represented on a digital elevation model, which proved to be important when studying natural hazards such as hydrological modelling in floodplains.

Anthropogenic landforms in an urbanising watershed in Virginia (USA) were also analysed in their study by Chirico et al. (2021). They point out the importance of the mapping of anthropogenic landform changes using historical aerial photographs, since the knowledge of these changes provides information that is essential for land management and also hazard identification. Mandarino et al. (2021) used bibliographic research, previous researches summarisation, and photograph interpretation in a GIS environment to map anthropogenic landforms and geo-hydrological hazards of the Bisagno Stream catchment in Italy. Also, Mossa et al. (2017) used, among others, historical aerial photographs, LiDAR, and topographic maps to map anthropogenic landforms and stream channel modifications in Georgia (USA) in the context of urbanisation. Spatial and quantitative changes in anthropogenic landforms can also be determined from archival maps. Szypula (2020) used topographic and geomorphological maps from the period 1883–2014 to analyse landforms in the Upper Silesian Industrial Region in Poland at a scale of 1:50,000. Human-influenced landscapes and anthropogenic landforms in urbanised areas (Rome, Italy) were studied by Luberti and Del Monte (2020). For their research they used a multi-temporal analysis of historical and archaeological maps using GIS software. They complemented their study by examining archival documents and reports, and were thus able to uncover three millennia of landscaping related to the construction of the earliest city walls. The anthropogenic forms of the alluvial plain in north-western Italy are described in Brandolini et al. (2021). The identification and mapping of morphological changes was carried out based on the comparison of historical and contemporary maps and aerial photographs.

Another suitable information source for mapping anthropogenic landforms is LiDAR. Ninfo et al. (2016) used LiDAR data to map anthropogenic landforms in urbanised landscapes. In this way, the morphology of a multi-layered archaeological mound in the centre of Padua (Italy) could be described in detail. The research results were used for flood risk prevention and archaeological prediction. LiDAR data were also used by Waga et al. (2022) to map anthropogenic landforms in a forested landscape in Poland. They identified landforms of different ages documenting various human activities, including the remains of afforestation, expansion and modification of water structures and road infrastructure, charcoal burning and tar distillation, mineral extraction and military activity. The airborne LiDAR-based digital terrain model (DTM) was used by Jancewicz et al. (2020) to create a map of mining and industrial anthropogenic landforms in Walbrzych (Poland). Geodetic methods, including GSP methods, and satellite radar interferometry have also been used to detect mining surface deformations in the Upper Silesian Coal Basin (Dulias, 2016). Henselowsky et al. (2021) used historical maps from the first geodetic mapping in 1893, Shuttle Radar Topography Mission (SRTM)-data from 2000 and high-resolution LiDAR DEM from 2015 with 1 m pixel resolution to map landform changes and to detect anthropogenic landforms in the Rhenish mining area in Germany (open lignite mining). Around the world, measured data are also used to determine the magnitude of subsidence as a result of deep coal mining, e.g. in Indonesia (Sasaoka et. al, 2015) or China (Quanyuan et al., 2009).

3. Materials and methods

3.1 Study area

Anthropogenic landforms related to mining activities were observed in 13 cadastral areas (Fig. 1) in the Karviná (eastern) part of the Ostrava-Karviná mining district. The total area is 111.45 km^2.

The Ostrava-Karviná mining district is the chief hard coal district in the territory of the Czech Republic. It forms a southern part of the Upper Silesian Coal Basin, a larger part of which lies in neighbouring Poland (Machač & Langrová, 2003). The selected area is a typical mining region in which long-term hard coal underground mining initiated in the 1930s has had many impacts on the landscape. More significant geomorphological changes can be identified in the Karviná part of the OKMD, rather than in the region of Ostrava. Coal was extracted in 20 deep mines here, out of which two remain still active: ČSM-Sever Mine and ČSM-Jih Mine.

3.2 Data and data processing

Spatio-temporal changes of anthropogenic landforms were mapped from aerial photographs at a scale of 1:5,000. Black and white aerial images from 1947, 1966, 1971, 1985, and 1994 were provided by the Office of Military Geography and Hydrometeorology in Dobruška. The scale of the images ranged from 1:11,000 to 1:30,000. The photographs were scanned in the resolution of 600 dpi. The geometric correction was performed in the PCI Geomatica Orthoengine software (Popelková & Mulková, 2016). The RMS value reached 3 m in the case of some images, which had no effect in shifts or deformations of geometrically corrected images. Geometrically corrected images were then joined in a mosaic. For the years 2009 and 2018, we used colour orthophotos in the S-JTSK coordinate system displayed via ArcGIS Server of the State Administration of Land Surveying and Cadastre.

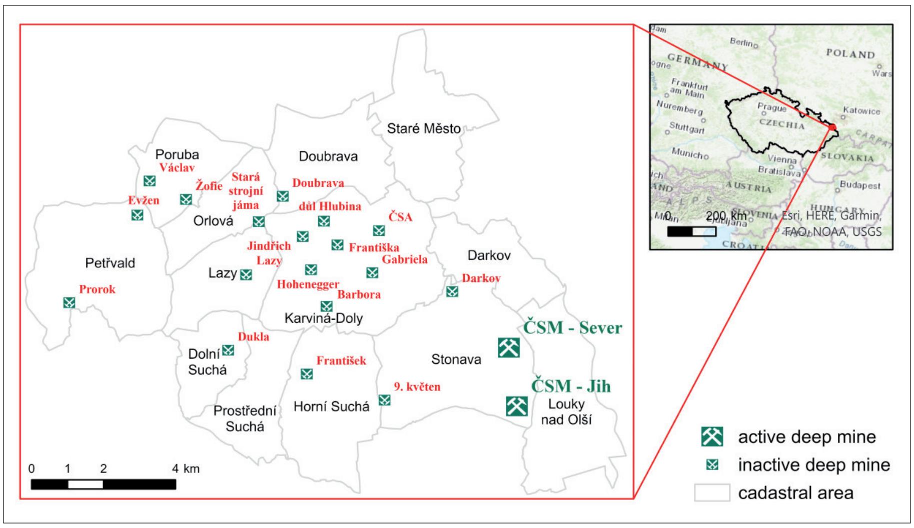

Fig. 1: Location of the study area within the Czech Republic
Source: Authors' elaboration, cadastral area from: Data ArcČR © ČÚZK, ČSÚ, ARCDATA PRAHA 2022. Basemap of software ArcGIS Pro World Topographic Map

3.3 Methods

Selected photographs and non-specific spectral signatures of individual landforms do not allow automatic image classification. Therefore, to evaluate the content of an image, standard procedures of visual interpretation were used (Jensen, 2007; Mulková & Popelková, 2013; Popelková & Mulková, 2016). We interpreted both primary displays of underground hard coal mining (waste heaps, submerged ground subsidence, tailings ponds, manipulation areas) and secondary displays (reclamation areas, communication landforms) (Mulková & Popelková, 2013). For the study area, we created a geodatabase with Feature Datasets for individual years that contained layers of landforms for each cadastral area. Created vector layers of landforms became the basis for the analytical processing of spatio-temporal development of observed landforms. Overlay operations were used to identify areas that remained unchanged as for the types of anthropogenic landforms and those that changed in the chosen period. Overlay operations also made it possible to determine the age of individual landforms, or more precisely, the observed year in which given anthropogenic landform occurs in the landscape. The processing and analysis of vector data was performed in the ArcGIS 10 software.

4. Results

The total area and number of anthropogenic landforms increased over the period of observation, with the largest increase in area between 1947 and 1966, and between 1971 and 1985 (Tab. 1). In 2018, we interpreted 382 anthropogenic landforms within 11.4% of the total study area. The largest area was represented by reclamation zones, tailings ponds, and submerged ground subsidence, occupying 77.2% of the total landform area. Anthropogenic landforms occupied the largest area in Karviná-Doly (394.29 ha; 24.1% of the cadastre area), Louky nad Olší (233.09 ha; 23.6%), Doubrava (125.18 ha; 16.1%), and Lazy (103.45 ha; 17.4%).

The position of the selected anthropogenic landforms described below in the text is shown in the Figure 2.

Name of landform	1947		1966		1971		1985		1994		2009		2018	
	No.	ha	No.	ha	No.	ha	No.	ha	No.	ha	No.	ha	No.	ha
Tailings ponds	22	14.02	40	136.08	41	187.75	80	430.74	96	536.32	80	379.49	94	365.72
Communication embankments	–	–	–	–	18	29.21	22	53.36	30	65.29	31	60.32	36	61.39
Manipulation areas	13	35.86	15	55.15	17	54.80	17	62.24	15	52.16	17	37.93	19	42.65
Embankments	–	–	–	–	–	–	–	–	3	4.18	3	2.90	3	3.68
Waste heaps	37	82.04	37	121.33	38	140.26	38	205.54	24	165.23	28	168.55	28	182.57
Opencast mining	5	46.88	2	33.07	2	26.59	1	7.93	–	–	–	–	–	–
Reclamation areas	–	–	–	–	3	5.50	15	74.82	15	128.75	61	372.16	58	400.32
Submerged subsidence	50	20.29	99	130.66	98	154.52	109	159.38	140	130.76	142	166.96	144	215.17
TOTAL	129	199.67	193	476.30	217	598.63	282	994.02	323	1,082.69	362	1,188.31	382	1,271.50

Tab. 1: Number of anthropogenic landforms and their total area within the whole study area in individual years. Source: Authors' calculations

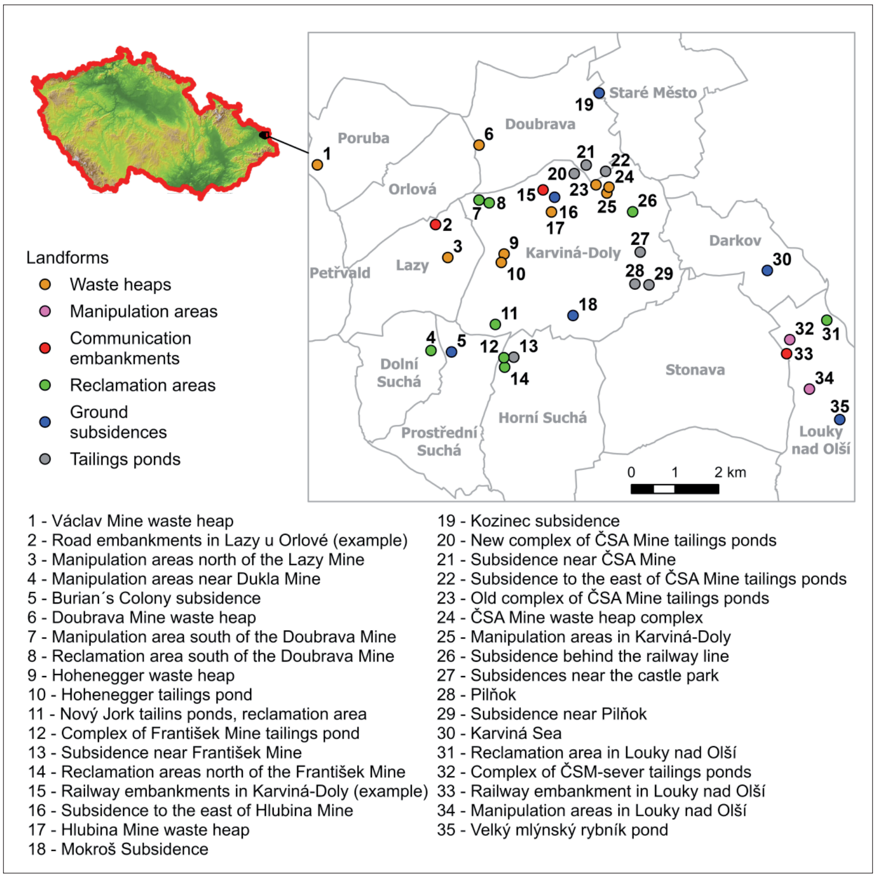

Fig. 2: The position of the selected anthropogenic landforms
Source: Authors' elaboration, cadastral area from: Data ArcČR © ČÚZK, ČSÚ, ARCDATA PRAHA 2022. Basemap of software ArcGIS Pro World Topographic Map

4.1 Development of mining landforms

4.1.1 Waste heaps

Waste heaps represent convex landforms that originate by the storage of tailings, i.e. non-recoverable waste material left over after underground extraction of hard coal. Their area can reach from a few ares to tens of hectares (Havrlant, 1980). The following types of waste heaps were mapped in the study area: waste piles, plate-shaped waste banks, terrace-like waste banks, side-hill waste heaps, ridge waste heaps, valley-fill waste heaps or their combinations. Waste heaps are usually located in the proximity of mine buildings, except for levelling heaps that are dumped in sites of sloping terrain. Active waste heaps in the photos represent vegetation-free surfaces with clearly visible contours. Over time, waste heaps become affected by natural geomorphic evolution processes (Szabó et al., 2010).

In 1947, waste heaps represented the most frequent mining landform that occupied 37.5% of the area of all anthropogenic landforms. A relatively high number of waste heaps occurred in the areas with more intensive extraction: Karviná-Doly (37.42 ha) and Lazy (11.46 ha). In 1966–2018, waste heaps occupied the largest area in Karviná-Doly and Doubrava. Increasing mining intensity affected the area of waste heaps up to the year 1985. From 1985 to 1994 the area of waste heaps decreased (Tab.1). A slight increase was identified in 2009 and 2018. In connection with the increasing occurrence of submerged ground subsidence and tailings ponds in 1966, and since 2009 also due to an increase in reclamation areas, waste heaps no longer belonged to dominant anthropogenic landforms of the study area.

The vastest waste heaps in the whole area of interest in 1947–1971 was the waste heap of the Doubrava Mine, the maximum area of which was 24 ha (Tab. 2). A side-hill waste heap was accumulated in a depression with the elevation difference of 20 m towards the surrounding terrain; its northern part is of a terrace-like character (Havrlant, 1980). In 1994, the western part of this waste heap became covered by self-seeding plants, while the eastern part remained devoid of vegetation. In 2009, amusement Dinopark was established in the eastern part of the waste heap body. The western part is largely covered by a forest, while the remaining area is grassy.

Since 1985, the largest waste heap (34.97 ha) in the study area has been the heap of the Hohenegger Mine (Fig. 3). In 1971 and 1985, it was constituted by a relatively complex body in a form of a table-like heap with significant terraces in its northern part. As a result, there was a distinctive formation in the landscape of the elevation difference of c. 25 m (Havrlant, 1980). By 1994, the area increased to 49.93 ha. The top part of the waste heap has been reclaimed to arable land. There is also an airfield for modellers. The planting of trees is visible on the slopes.

The third largest waste heap of the study area in 1966 and 1971 was the heap (11 ha) of the Václav Mine in Poruba. In its northern part, it is a prolonged ridge, whereas the southern part was disrupted by waste rock removal and new heaping up (Havrlant, 1980). The elevation difference, as compared to the surrounding terrain, is more than 20 m. At present, the heap is forested.

Another relatively large waste heap complex worth mentioning is to the north of the ČSA Mine in Karviná-Doly. In 1966, it was constituted by a heap-like unit or a table-like unit. Since 1985 it has been the second largest waste heap complex. In 2018, it was formed by 4 units. The south-eastern part was partly reclaimed as a result of tree planting on the slopes of the heap. The complex is mainly a table with irregular heap peaks covered by smaller heaps or tables.

4.1.2 Submerged ground subsidence

Ground subsidence originates as a result of the surface subsidence above the mined-out space. The size depends on geological conditions, tectonics, and the area and thickness of coal seams (Havrlant, 1980). The subsidence can be filled with water. In the aerial images, only submerged ground subsidence can be easily identified. In comparison with other water surfaces, submerged ground subsidence usually has an irregular broken shape that is given by relief formation at the site of flooding. In most cases, the shape and area of submerged ground subsidence are subject to temporal changes due to ongoing surface subsidence.

Waste heap	Area (ha)						
	1947	1966	1971	1985	1994	2009	2018
Doubrava Mine waste heap	12.62	24.09	24.30	23.82	23.11	23.59	23.59
Hlubina Mine waste heap	6.57	–	–	–	–	–	–
Hohenegger waste heap	5.66	16.66	19.54	34.97	49.92	49.92	49.92
Václav Mine waste heap	3.91	11.29	11.00	10.92	5.58	5.58	5.58
ČSA Mine waste heap complex	5.53	12.54	16.85	34.38	36.93	35.83	38.75

Tab. 2: Area of the largest waste heaps in individual years. Source: Authors' calculations

Fig. 3: Hohenegger waste heap in aerial photos from 1971 and 2018
Sources: The photo was provided by the Military Geography and Hydrometeorology Office in Dobruška. © MO ČR/GeoSI AČR. Orthophoto (2018), map services of ČÚZK (State Administration of Land Surveying and Cadastre)

Aerial images of 1947 revealed 50 areas of submerged ground subsidence (10.2% of all anthropogenic landforms). The largest areas of the submerged ground subsidence were in Karviná-Doly (13.66 ha), Doubrava (5.63 ha), and Horní Suchá (2.12 ha). The very largest submerged ground subsidence (3.27 ha) was found in Doubrava, to the north of the ČSA Mine (Tab. 3).

The images of 1966 showed a significant increase in submerged ground subsidence that comprised 27.4% of all anthropogenic landforms within the study area (Tab. 1). The total area of the subsidence continued to grow by 1985. However, its share in the total area of anthropogenic landforms decreased to 16.0%. After a decrease in the area of submerged ground subsidence identified from images of 1994, there was a renewed increase of the area. In 2018 submerged ground subsidence constituted 16.9% of all anthropogenic landforms.

Based on the images of 1994, the territory most affected by undermining and subsequent flooding of ground subsidence was that of Karviná-Doly. In 1971, there was 63.9% of all submerged ground subsidence that occupied 98.80 ha. Towards the year 1994, the area decreased to 39.08 ha. Another significant occurrence of submerged ground subsidence was mapped in 1966 in Horní Suchá (15.62 ha) and Prostřední Suchá (11.67 ha) and in 1971 also in Lazy (12.50 ha). These were newly identified in 1985 in Darkov (8.45 ha) and in Louky nad Olší (14.05 ha), whereas their area continued to increase in the following years. In 2009 and 2018, these are the areas where undermining was most manifested by the creation of submerged ground subsidence. In 2018, the largest areas were revealed in Darkov (44.27 ha), Louky nad Olší (40.37 ha), and Doubrava (39.45 ha).

In 1966, the largest submerged ground subsidence was found near the present-day Pilňok tailings pond in the south-eastern part of Karviná-Doly (Tab. 3). The second largest submerged ground subsidence was located to the north of the František Mine in Horní Suchá. A vast territory of 11 submerged ground subsidence areas (22.85 ha) was identified to the southeast of the ČSA Mine, namely at the place where there used to be sports complexes and a castle park in 1947. In 1971, the devastating effects of undermining were also connected to the area expansion of this submerged ground subsidence. Four other areas of submerged ground subsidence were found to the north of this complex, behind the railway line, with the area of 11.82 ha. By 1971, this area decreased due to filling the basins with tailings.

In 1985, the largest submerged ground subsidence was found to the east of the surface constructions of the Dukla Mine, at the place of Burian's Colony along the borderline of Dolní Suchá and Prostřední Suchá. Next in the ranking was the submerged ground subsidence at the place of a former castle park in Karviná-Doly and to the east of tailings ponds of the ČSA Mine on the border of Karviná-Doly and Doubrava.

In 1994, the largest submerged ground subsidence was Mokroš in Karviná-Doly, to the southeast of the Barbora Mine. It was followed by the submerged ground subsidence at the site of Burian's Colony, and in Darkov, at the site of nowadays Karviná Sea (Fig. 4). The area of the Karviná Sea increased to 33.30 ha in 2018. In 2009, it was the largest submerged ground subsidence. The second largest submerged ground subsidence in 2009 was the former pond named Velký mlýnský rybník in Louky nad Olší (18.38 ha). New submerged ground subsidence originated on the border of Doubrava and Staré Město in the locality of Kozinec. Along with the neighbouring submerged ground subsidence, the total area of submerged ground subsidence Kozinec was 47.17 ha in 2018.

Subsidence	Area (ha)						
	1947	1966	1971	1985	1994	2009	2018
Subsidence near ČSA Mine	3.27	–	–	–	–	–	–
Subsidence near František Mine	1.51	14.28	–	–	–	–	–
Subsidence to the east of Hlubina Mine	2.81	–	–	–	–	–	–
Subsidence near Pilňok	0.00	15.60	21.10	–	–	–	–
Subsidence near the castle park	1.22	22.85	42.93	14.93	–	–	–
Subsidence behind the railway line (Karviná-Doly)	0.25	11.82	6.29	4.75	0.58	0.33	0.35
Burian's Colony subsidence	–	3.68	7.81	17.05	12.18	5.20	5.87
Subsidence to the east of ČSA Mine tailings ponds	–	2.10	3.84	9.46	–	–	–
Mokroš subsidence	1.28	5.09	–	–	10.29	9.87	10.25
Karviná Sea	–	–	–	–	7.93	31.28	33.30
Velký mlýnský rybník pond	–	–	–	–	5.77	18.38	21.16
Kozinec subsidence	–	–	–	–	–	15.23	47.17

Tab. 3: Area of the largest submerged ground subsidence. Source: Authors' calculations

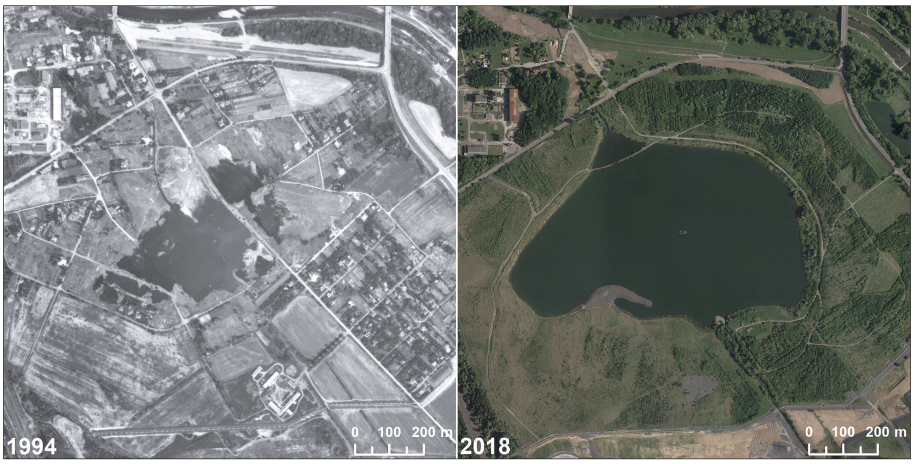

Fig. 4: Karviná Sea in aerial photos from 1994 and 2018
Sources: The photo was provided by the Military Geography and Hydrometeorology Office in Dobruška. © MO ČR/GeoSI AČR. Orthophoto (2018), map services of ČÚZK (State Administration of Land Surveying and Cadastre)

4.1.3 Tailings ponds

Tailings ponds are used for permanent or temporary storage of hydraulically transported tailings (Kirchner & Smolová, 2010). They are either artificially created, or they are already existing water areas such as submerged ground subsidence. Unlike submerged ground subsidence, tailings ponds usually have a regular geometrical shape. They are found close to surface constructions of mines. In aerial photos, we observe well visible embankments in the vicinity of many tailings ponds. The aerial images also show dry tailings ponds in cases where the service life of tailings ponds has ended. These dry tailings ponds are shallow concave landform shapes filled with tailings that are gradually reclaimed, or they become overgrown with airborne vegetation.

In the study area, tailings ponds are large anthropogenic landforms. The smallest area covered by tailings ponds was recorded within the study area in 1947 (Tab. 1). The largest system of tailings ponds originated to the north of ČSA Mine at the place of today's waste heap and on the top of the Hohenegger waste heap. From 1947 to 1994, the area of tailings ponds increased rapidly. The largest extent was mapped in 1994 when a total of 96 tailings ponds occupied 49.5% of the area of all anthropogenic landforms. By 2018, following the decline in coal mining and subsequent reclamations, the extent of tailings ponds dropped. The highest number of tailings ponds was observed in Karviná-Doly with the maximum number in 1994 (218.1 ha). In Louky nad Olší, tailings ponds appeared in aerial images as late as 1985. It is the area with the second highest representation of tailings ponds in 1994 when their extent reached its maximum (86.04 ha). In Doubrava, tailings ponds appear in images starting in 1966 with the maximum area in 1994 (51.86 ha).

In 1966, the largest tailings ponds complex was found to the north of the ČSA Mine in Karviná-Doly. The maximum extent of this complex was recorded in 1994 (Tab. 4). In 1994, two largest tailings ponds were identified in Karviná-Doly. The first one formed a part of a complex of three tailings ponds in the Pilňok locality which had contained submerged ground subsidence by 1971. The extent of the largest Pilňok tailings pond was 54.16 ha. The second largest tailings pond was Nový Jork to the southwest of the Barbora Mine. Both of these localities were first captured in the aerial images of 1985. By 2018, the extent of tailings ponds in both localities had decreased due to reclamation activities (Tab. 4).

From 1985, the second largest complex of tailings ponds was found to the east of the ČSM-Sever Mine (Fig. 5). In 1994, this complex comprised five tailings ponds of maximum area 96.44 ha. In 2018, the complex contained 13 tailings ponds with the total area 80.89 ha, out of which 25 ha was reclaimed.

4.1.4 Manipulation areas

Manipulation area is a type of complex surface created by convex and concave shapes of various dimensions and typically containing unpaved roads. Manipulation areas are generally found in the proximity of mine buildings, tailings ponds, or waste heaps where they perform the service and transport functions. Manipulation areas demonstrated the least extent in 1947. From this year onwards, it went increasing, reaching its maximum in 1985 (Tab. 1). In 1947, the largest manipulation areas were those in Dolní Suchá (13.82 ha). They were connected to the surface buildings of the Dukla Mine in the east. In 1966, 1971, 1985, and 2009, manipulation areas were the largest in Karviná-Doly, with the maximum in 1966 (31.01 ha). There, the very largest manipulation area was to the south of the Doubrava Mine (7.37 ha). In 1994, the largest number of manipulation areas in Lazy (14.18 ha) north of the Lazy Mine was mapped. In 2018, most manipulation areas were found in Louky nad Olší, and they covered the area of 15.33 ha to the east of ČSM-Sever and ČSM-Jih Mines, in the vicinity of tailings ponds and Bohumín-Čadca railway line.

Tailings ponds	Area (ha)						
	1947	1966	1971	1985	1994	2009	2018
Old complex of ČSA Mine tailings ponds	4.71	4.49	1.64	–	–	–	–
Hohenegger tailings pond	4.19	–	–	–	–	–	–
New complex of ČSA Mine tailings ponds	–	74.54	86.21	110.87	115.55	94.51	95.71
Pilňok	–	–	–	49.55	66.28	38.61	38.09
Nový Jork	–	–	–	29.53	32.64	7.93	5.65
Complex of František Mine tailings pond	–	10.72	43.08	61.09	63.77	30.76	29.72
Complex of ČSM-Sever tailings ponds	–	–	–	75.93	96.44	88.35	80.89

Tab. 4: Areas of the largest tailings ponds
Source: Authors' calculations

Fig. 5: Complex of ČSM-Sever tailings ponds in aerial photos from 1994 and 2018
Sources: The photo was provided by the Military Geography and Hydrometeorology Office in Dobruška (© MO ČR/GeoSI AČR), Orthophoto (2018), map services of ČÚZK (State Administration of Land Surveying and Cadastre)

4.1.5 Reclamation areas

Reclamation areas are convex landforms that resemble low flat waste heaps. They originate as a part of reclamation buildings. Unlike waste heaps, they can be found quite far from mine surface buildings. Visual interpretation requires support data to differentiate reclamation areas from waste heaps. Reclamation areas were first identified in images from 1971 in Karviná-Doly and Horní Suchá that originated to level subsided terrain. The size of reclamation areas increased by 2018 with a slightly more significant increase in 2009 when 61 reclamation areas occupied 31.3% of the total area of all anthropogenic landforms (Tab. 1). In 2009, reclamation areas were most expanded in Karviná-Doly (87.36 ha), Louky nad Olší (78.36 ha) and Horní Suchá (44.52 ha). The larger ones were observed in Karviná-Doly, at the place of tailings ponds to the west of the Barbora Mine in the locality of Nový Jork (28.41 ha), and to the south of the Doubrava Mine, at the place of former tailings ponds (42.55 ha). In Louky nad Olší, a vast reclamation area was mapped to the east of the ČSM-Sever Mine with an overlap to Darkov (Fig. 6). Ten reclamation areas were recorded on the area of 84.71 ha at a place of a subsided locality. In Horní Suchá, the reclamation concerned tailings ponds and submerged ground subsidence to the north of the František Mine.

In 2018, reclamation areas belonged to the largest anthropogenic landforms occupying 31.5% of the area of all anthropogenic landforms. The largest reclamation area was in Louky nad Olší (90.58 ha), where reclamation took place to the east of the ČSM-Sever Mine.

Fig. 6: Reclamation areas to the east of the ČSM-Sever Mine in aerial photos from 2009 and 2018
Source: Map services of ČÚZK (State Administration of Land Surveying and Cadastre)

4.1.6 Communication landforms

Communication landforms, which were created as a result of deep mining, were visually interpreted from aerial images. In such a case, they serve to level subsidence destroying roads. Communication landforms are convex line landforms of sometimes even a few metres in height. The following landforms were distinguished: railway embankments, road embankments, and embankments of engineering networks. Communication landforms were first observed in images from 1971. Their size increased by 1994 (Tab. 1). They were railway embankments of the original Košice-Bohumín railway and rail sidings leading to mines, embankments on Ostrava-Karviná road or Orlová-Havířov road.

In 1971, 69.5% (20.29 ha) of all communication landforms within the study area was related to Karviná-Doly followed by Louky nad Olší (3.35 ha) and Lazy (2.17 ha). The size of communication landforms within these cadastral areas remains the largest in the whole study area as late as 2018. In 2018, communication landforms covered 24.11 ha in Karviná-Doly, 17.6 ha in Louky nad Olší, and 10.69 ha in Lazy. The mapping of these landforms comprised mainly railway embankments under rail sidings leading to mines and those on Bohumín-Čadca railway No. 320, namely in Louky nad Olší, where there are two largest embankments of 17.16 ha.

4.2 Analysis of spatio-temporal changes of anthropogenic landforms

We used analytical tools of GIS software to identify areas where anthropogenic landforms remained unchanged in a selected period. It was thus possible to determine the age of landforms within the studied period (Fig. 7). It is not possible to determine from Figure 7 what type of anthropogenic landform is found in specific parts of the locality. The age of individual landforms is shown in the Figure 8 on the example of the Lazy cadastral area. Total areas containing identical anthropogenic landforms between individual time intervals of the study period of 1947–2018 are given in Table 5.

In the observed period 1947–2018, identical anthropogenic landforms occur only on less than 24 ha. Those preserved most were waste heaps (22.73 ha). Most waste heaps were preserved at the boundary of Orlová and Doubrava (6 ha) and Karviná-Doly (5 ha). The total area of preserved submerged ground subsidence was just 1.08 ha. From 1966 to 2018, the preserved landforms included 80.67 ha of tailings ponds, 35.54 ha of waste heaps, 11.73 ha of submerged ground subsidence, and 1.67 ha of manipulation areas. The vastest tailings ponds (53 ha) remained preserved north of the ČSA Mine. Other largest areas preserved from 1966 comprise: a waste heap in Doubrava (9.80 ha) and tailings ponds in Prostřední Suchá (9.51 ha).

From 1971 to 2018, the most preserved landforms were waste heaps (26.60 ha), tailings ponds (23.82 ha) and communication landforms (18.24 ha). Lower figures are observed in connection with submerged ground subsidence (5.06 ha). The system of

Identical anthropogenic landform	Area		
	(ha)	(% total area)	(% landforms)
From 1947 to 2018	23.81	0.21	1.45
From 1966 to 2018	129.61	1.16	7.89
From 1971 to 2018	74.37	0.67	4.53
From 1985 to 2018	283.43	2.54	17.25
From 1994 to 2018	232.66	2.09	14.16
From 2009 to 2018	381.12	3.42	23.20

Tab. 5: Total areas of an identical anthropogenic landform in the period 1947–2018
Source: Authors' calculations

tailings ponds north of the ČSA Mine expanded since 1971 by additional areas with a total area of 9.57 ha. The above-mentioned tailings ponds in Prostřední Suchá were enlarged by 6.68 ha. The third largest anthropogenic landform preserved from 1971 to 2018 was an embankment in Karviná-Doly (5.99 ha).

When we disregard the last short time interval (2009–2018), most anthropogenic landforms were preserved from 1985. More than half of their extent is occupied by tailings ponds (155.77 ha) and less than a third of waste heaps (49.06 ha). These are followed by reclamation areas (31.61 ha), communication landforms (27.33 ha)

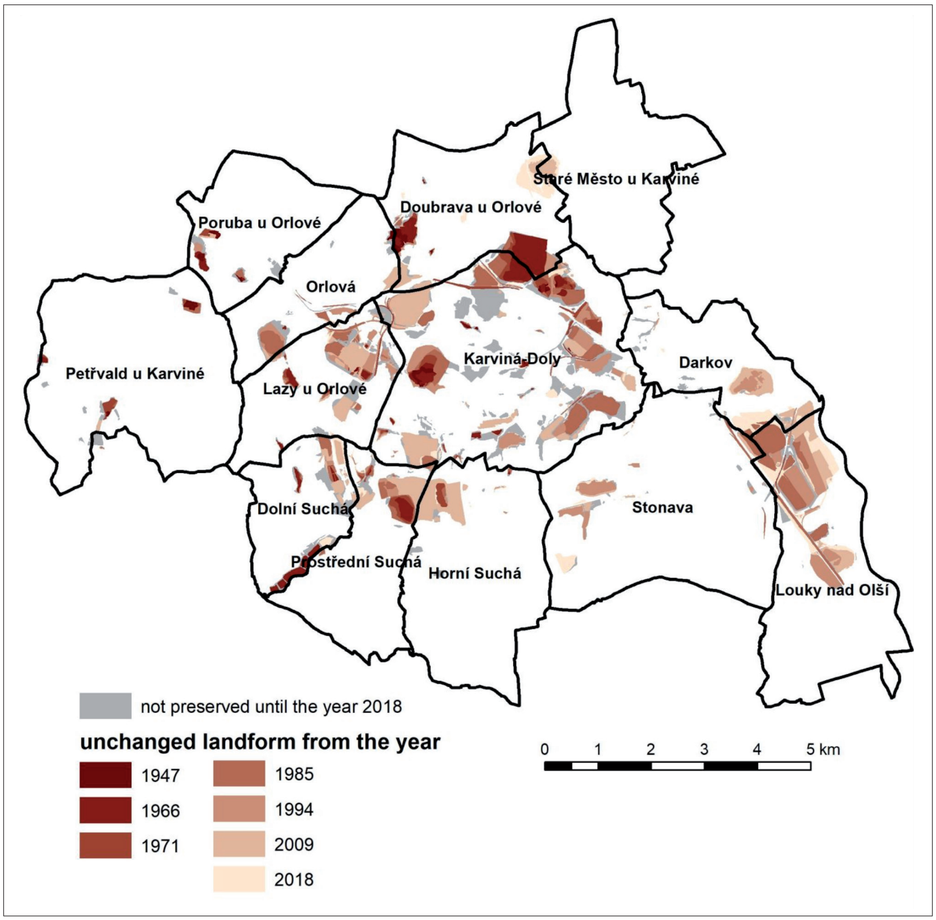

Fig. 7: The unchanged mining landforms within period 1947–2018 in Ostrava-Karviná mining district
Sources: Authors' elaboration, cadastral area from: Data ArcČR © ČÚZK, ČSÚ, ARCDATA PRAHA 2022

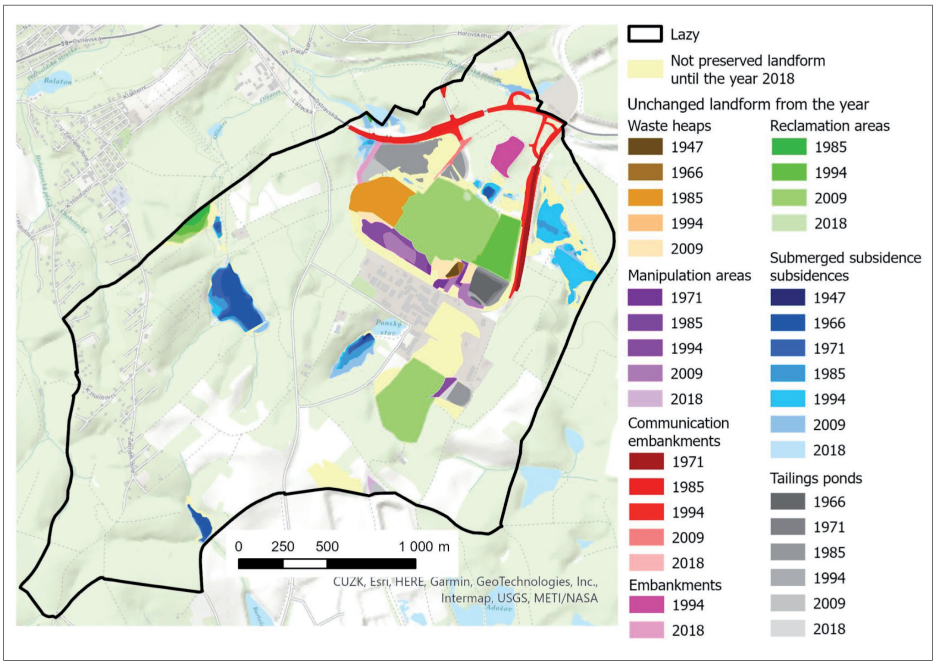

Fig. 8: The unchanged anthropogenic landforms in Lazy
Sources: Authors' elaboration, cadastral area of Lazy from: Data ArcČR © ČÚZK, ČSÚ, ARCDATA PRAHA 2022. Basemap of software ArcGIS Pro World Topographic Map

and submerged ground subsidence (19.31 ha). The vastest group of tailings ponds occurs north of Louky nad Olší (39.73 ha). Next come two tailings ponds parallel to each other in Karviná-Doly (34.11 ha), a tailings pond in Louky nad Olší (15.58 ha) and a reclamation area in Orlová (15.01 ha).

Some submerged ground subsidence turned into tailings ponds in the following observed period. In each period of those from 1947 to 1994, this represents the largest difference in connection with the studied anthropogenic landforms. For example, 8.55 ha of submerged ground subsidence from 1947 were used as tailings ponds in 1966; in the following periods, this change has a growing trend: 23.38 ha (1966–1971) and 48.79 ha (1971–1985). Most submerged ground subsidence (50.72 ha) turned into tailings ponds in 1985–1994.

From 1985, changes in anthropogenic landforms from reclamation dominated. The most significant change in all studied periods is the transformation of 105.36 ha of tailings ponds into reclamation areas in 1994–2009. The same change, yet to a smaller extent (12.51 ha), dominates the period 2009–2018. Submerged ground subsidence was reclaimed as well: 16.81 ha in 1971–1985, 14.93 ha in 1985–1994, and 11.44 ha in 1994–2009. Reclamation also took place in areas of mineral extraction and in manipulation areas. Another frequent change was using original manipulation areas as waste heaps, predominantly on 18.04 ha in 1985–1994.

5. Discussion

5.1 Landform dynamics

The analysis of spatio-temporal development of mining landforms using the photointerpretation of aerial images is a suitable tool in capturing the dynamics of such landforms in a quickly transforming mining landscape. The changes in these anthropogenic landforms are related to the main driving force in the study area – industrialisation. Industrialisation, which started to form the structure of the Karviná landscape in the 1850s, was further reinforced by the political development of former Czechoslovakia after 1948. Newly emerging mining anthropogenic landforms that significantly transform the relief and the landscape structure persist in the landscape for either a short or long period. The longest persisting mining landforms are related to mineral extraction (Migoń & Latocha, 2017).

The most distinctive convex landforms in the mining landscape are waste heaps. In 1947, waste heaps occupied more than a third of all anthropogenic landforms in the study area. In 1971, waste heaps were located on 1.26% of the total area, whereas in the Ruhr District their proportion is only 0.02% (Harnischmacher, 2007). The total extent of waste heaps increased by 1985 in connection with increasing mining activities. Mineral extraction reached its peak between 1979 and 1985, with the extraction volume exceeding 16 million tons of hard coal per year (Martinec et al., 2006). The vastest waste heap area was identified in Karviná-Doly, Doubrava and Lazy. The increased emergence of waste heaps was also reflected by primary evidence of heaps in 1956 (Popelka, 2013), with the biggest concentration of tailings heaps occurring in Karviná-Doly. The spatio-temporal analysis shows that the most preserved landforms in the studied period of 1947–2018 were waste heaps. However, some waste heaps ceased to exist due to tailings extraction for the construction of roads and dam barriers and regulation of the waters (Drlík, 1964). Since the 1960s, tailings were gradually more and more used for large-scale filling of ground subsidence within targeted reclamation processes. Therefore, the extent of waste heaps identified in aerial images after 1985 decreased accordingly. The share of waste heaps in the total area decreased from 1.84% in 1985 to 1.48% in 1994. Compared to the Polish part of the Upper Silesian Coal Basin, where this share was 0.91% in 1993 (Dulias, 2016), the representation of waste heaps in the area of interest is higher. In 2018, waste heaps were located on 1.64% of the total area, while in Walbrzych their share was 3.05%.

A typical display of deep mining is ground subsidence. Terrain movements cause grave damage to buildings, infrastructure and soils, and in the case of vast subsidence, as in the Karviná region, they can lead to significant territory devastation. The total area of ground subsidence from the beginning of the mining activities cannot be specified scientifically due to the lack of systematic observation until 1960. The maximum total subsidence in the Karviná region is estimated at 40 metres in depth. Long-term and strong subsidence affected, for instance, the Church of St. Peter from Alcantara in Karviná (which subsided by almost 33 metres from 1950), or the building of the railway station in Karviná-Doly (which subsided by 30 metres from the beginning of the 1970s to the mid-1990s) (Havrlant, 1997b).

Submerged ground subsidence was recorded in the study area as early as 1947, and their total extent went increasing up to the present time. By 1994, submerged ground subsidence was most prevalent in Karviná-Doly. In 2018, they were of the largest area in Darkov, Louky nad Olší and Doubrava. Some submerged ground subsidence was used in tailings management from the second half of the 20th century (Havrlant, 1980). These dynamic changes can be documented by the spatio-temporal analysis of aerial photographs of 1947–1994, with the highest increase between 1985 and 1994.

Tailings ponds in the Karviná Region appeared largely as late as in the second half of the 20th century in connection with the development of hard coal treatment technology as in the 1950s a problem arose regarding a large amount of fine-grained waste. During the following decades (up to 1994), the area of tailings ponds increased rapidly. Towards the year 2018, however, their area decreased due to a gradual decline of mining, changes in the coal treatment technology and reclamation activities. Most tailings ponds were mapped in Karviná-Doly, Louky nad Olší and Doubrava, with the maximum in 1994.

From the 1990s, the tailings ponds were gradually mined, mainly for energy purposes. The disappearance of tailings ponds as a result of reclamation with a maximum in the period 1994–2009 and then in 2009–2018 is also confirmed by the analysis of aerial photos. Afterwards, biologically precious wetlands and bodies of water formed in the place of reclaimed tailings ponds (Hlavatá et al., 2012). In 2018, the share of tailings ponds in the total area was 3.28%. Of these, 1.98% were water-filled tailings ponds. In Walbrzych, the share of tailings ponds was 0.71% of the total area (Jancewicz et al., 2020).

The formation of submerged ground subsidence and tailings ponds leads to an increase of water areas in the mining landscape. This phenomenon is described by Rzętała and Jaguś (2012) in the Upper Silesian region and surrounding areas. The Upper Silesian Anthropogenic Lake District (6,766 km^2) consists of 4,773 water bodies of various origins, including submerged ground subsidence. The lake density of the Lake District is 2.74%. In Karviná part of OKMD, the lake density was 3.71% in 2018. The area of submerged ground subsidence and tailings ponds was included. Other water areas were not considered. The area of manipulation areas increased due to increasing mining up to 1985, and then it started to decrease after 2009.

Reclamation areas and communication embankments started to appear in the study area in 1971. Efforts to reclaim the landscape affected by mining made it possible for reclamation areas to enlarge up to the last studied year. The extent of communication embankments increased by 1994. Most communication embankments, manipulation areas and reclamations areas were identified in Karviná-Doly. If we focused on communication embankments as line forms and if we observed other linear anthropogenic landforms, it would be interesting to statistically evaluate the data and compare them with the results of Szypula (2013) in the southern part of the Silesian Upland.

In 2018, the share of anthropogenic landforms was 11.41% of the total area in the Karviná part of OKMD. This value is higher than in the Polish part of the Upper Silesian Coal Basin, where anthropogenic landforms were located on 2.78% of the total area, i.e. almost 150 km^2 (Dulias, 2016). However, this proportion is comparable to the proportion of man-made landforms in Walbrzych, which is 12% of the entire coal mining zone area (Jancewicz et al., 2020).

5.2 Study limitations

Although aerial images represent a valuable source of information on the state of landscape at the time of aerial photography, it is necessary to consider input data when assessing the occurrence and development of anthropogenic landforms. Our analysis was based on aerial photos from eight observed years to capture the real state as much as possible. Some results can be distorted because of different intervals between individual data sets. We observed six periods: 1947–1966 (19 years), 1966–1971 (5 years), 1971–1985 (14 years), 1985–1994 (9 years), 1994–2009 (15 years) and 2009–2018 (9 years). The total extent and number of anthropogenic landforms increased the most in the long periods 1947–1966 and 1971–1985 (Tab. 2). The third longest period (1994–2009) was characterised by a decline in mining intensity. In the case of mining landscape, it is, therefore, more convenient to shorten time intervals in the period of intensive mining if it is allowed by the availability of aerial photographs.

Another limitation rests in the study of the flooding of subsided terrain followed by the occurrence of submerged ground subsidence, which, unlike dry subsidence, can visually be interpreted from aerial photographs. On the one hand, dry subsidence can be identified based on indirect photointerpretation signs such as the demolition of buildings, the devastation of agricultural areas, or changes in the road structure. However, we can hardly determine the size of dry subsidence due to missing elevation data. A necessary tool is a digital terrain model that would have to be made in the time of aerial photography to capture the current elevation conditions of the study area. To monitor the size of mining subsidence, we can use geodetic methods, differential InSAR (DInSAR) technique (Raucoules et al., 2003), GPS technique (Doležalová et al., 2009), a combination of GPS and DInSAR (Kadlečík et al., 2015) or GIS-based multi-factorial weighted spatial regression (Blachowski, 2016). Nevertheless, these methods can barely be applied retrospectively to determine the size of subsidence in the past.

6. Conclusion

Historical aerial photographs are a valuable source of information on the state of the landscape. An indisputable advantage of multi-temporal aerial photography is the possibility to make spatio-temporal analyses that capture the changes in individual landforms. Although previous studies performed terrain mapping of anthropogenic landforms in the study area, the assessment of landform development and age has so far not been conducted. The total extent and number of anthropogenic landforms in the study area increased the most in the periods 1947–1966 and 1971–1985. The largest area (1,271.5 ha) and number (382) of mining landforms was identified in 2018. The largest area was occupied by reclamation zones, tailings ponds, and submerged ground subsidence.

When studying the same type of anthropogenic landforms in our study, we found that these occurred on c. 24 ha in the entire study period 1947–2018. Waste heaps were the most preserved landforms in the studied period of 1947–2018. Submerged ground subsidence and tailings ponds showed a high dynamic of changes. In 2018, reclamation areas had the largest area. They were first detected in images from 1971. Most anthropogenic landforms (381 ha) remained preserved in the last observed period 2009–2018. In comparison with field mapping, visual interpretation may be performed in a relatively shorter time concerning the size of the study area. In this case, we can also ensure higher accuracy when determining the extent of individual landforms. Besides being an experienced interpreter, it is often necessary to be acquainted with the territory. It is desirable to use support resources to identify disputed objects in an image.

If we compare visual photointerpretation with the automatic image classification of the remote sensing method, a drawback is time demands. It is, however, a method that cannot effectively be substituted with digital image classification in the case of mapping mining landforms from historical aerial photographs. Apart from the information on the state of the landscape in a given year, data acquired by visual photointerpretation bring a potential for the analysis of spatio-temporal changes of anthropogenic landforms.

The study employs an interdisciplinary approach, utilising remote sensing data and geographic information systems tools in the field of anthropogenic geomorphology to monitor the status and historical evolution of anthropogenic landforms. This approach represents a synthesis of geomorphological mapping and geoinformatics, with necessary overlaps to other disciplines, such as historical geography and landscape ecology. The findings of the study are of interest not only to geomorphologists and landscape ecologists, but also to geoinformaticians, historians, geomorphologists and specialists engaged in spatial and landscape planning. Understanding landform dynamics provides key application in the reclamation of post-mining landscapes, where information on landforms stability and their suitability to enhance landscape structure and functions poses an essential challenge for consequent planning phases.

The study is also useful for comparison with the evolution of anthropogenic landforms in other areas affected by deep mining not only in Europe but also in non-European mining areas. Another research direction is to map spatio-temporal changes of anthropogenic landforms in the emerging post-mining landscape, complemented by morphometric analyses of anthropogenic landforms.

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