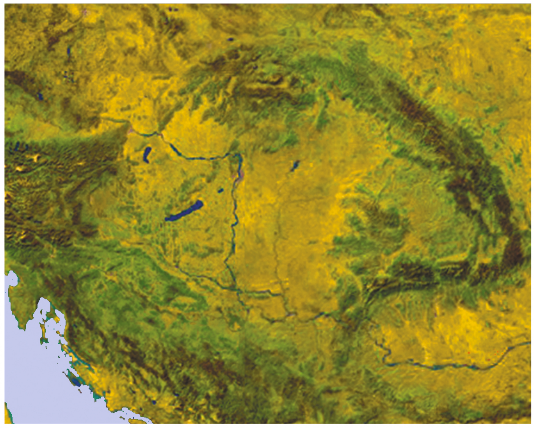
HUNGARIAN GEOGRAPHICAL BULLETIN



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Spatial extension of soil water regime variables derived from soil moisture values using geomorphological variables in Hungary

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Abstract

Accurate measurement and spatial extension of soil properties are essential in geoinformatics and precision agriculture for effective resource management, particularly irrigation planning. This study addresses the challenge of extending soil moisture data and related soil water regime variables in heterogeneous agricultural landscapes by integrating geomorphological variables (GVs) derived from high-resolution digital elevation models (DEM). In digital soil mapping, machine learning and geostatistical models often struggle with validation due to data scarcity and variability across space through many geographical regions that come from the point readings of soil properties. A different approach was developed in the form of a new methodology combining two hourly Sentek soil moisture measurements from the topsoil with DEM-derived GVs to model and extend soil water regime variables. The research was conducted on an agricultural field in a hilly area with diverse geomorphological variability. The model's performance was validated using cross-validation techniques. The monitoring and spatial extension results indicate that GVs enhance the spatial prediction of soil moisture, capturing periodic fluctuations in the upper soil layer more effectively by using in-situ, time series soil moisture sensor readings rather than traditional, on field, one time reading approaches. We observed that certain GVs, such as the slope, both type of curvatures and the convergence, were strong predictors of soil moisture variation, enabling the model to produce more accurate irrigation recommendations for agricultural areas with similar geomorphological areas. One of the soil water regime variables was validated during the preliminary validation with mixed results. The main issue was coming from the field use and spatial scarcity of the measurements. Our approach not only provides a different method for spatially extending the current soil water regime data but also offers a framework for improving irrigation decision-making with the help of other value rates and limit related soil regime variables derived from the time series readings from the soil moisture sensors. With its variables, the model allows for forecasts of soil moisture changes, which can inform better irrigation scheduling and water resource management, all based on data from the soil monitoring sensor system.

Keywords: soil moisture, water characteristics, soil water regime variables, geomorphology, GIS, machine learning, digital elevation model (DEM), precision agriculture

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Introduction

There is a significant demand for soil parameters that describe measured and derived soil properties, both from the agricultural sector and for climate-related research and decision support systems (Van de Broek, M. *et al.* 2019).

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In Hungary, while large-scale water resource maps are available for water management, hazards, and related uses, these resources operate only at a general scale (Laborczi, A. *et al.* 2020). This limits their utility in high-precision applications, especially when analyzing the impact of various small-scale landforms – micro-basins, shallow water bodies, or small-scale relief units – on irrigation needs and soil moisture retention. Precision agriculture, which addresses these challenges on a finer scale, has shown considerable promise in optimizing agricultural water management, yet substantial gaps remain in data granularity and methodology (Liang, Z. *et al.* 2020; Garcia, L.D. *et al*. 2023).

In general, traditional machine learning validations – such as dividing existing measured values into training and testing datasets – are difficult to implement due to the lack of localised soil measurements across different study areas. The scarcity and variability of numerical data complicate model validation and call for the development of customized validation methods. These methods should enable a robust assessment of the error magnitude between actual and estimated data. Furthermore, because spatial variables derived from terrain models are highly correlated with soil moisture properties, they hold strong potential for informing soil-related variables, especially those concerning soil water regimes (Dobos, E. *et al.* 2000; Dobos, E. and Daroussin, J. 2005; Olaya, V. and Conrad, O. 2009; Hartemink, A.E. 2015; Mehrnaz, N. *et al.* 2021; Senanayake, I.P. *et al.* 2024).

In addition to spatial surface properties, precision irrigation decision-making traditionally relies on water tension measurements and pF pressure curves, which indicate the pressure required by plants to uptake water under varying moisture conditions (Liang, Z. *et al.* 2020; Lakhiar, I.A. *et al.* 2024). This study, however, introduces a novel approach that incorporates the volume percentage of soil moisture along with the rates of wetting and drying to guide irrigation timing and quantity. While this research does not seek to replace traditional water tension methods, it expands upon them by providing a complementary methodology to improve decision-making for precise agricultural irrigation. Through this, we also aim to highlight the usability of advanced soil monitoring devices, which can be effectively applied within the proposed framework.

Key goals that the current research went for integrating machine learning with spatial interpolation techniques, such as Regression Kriging, to better predict soil moisture variability at smaller scales for water management and complementing pF curves, traditional water tension metrics methodology with time-series soil moisture volume percentages to support controlled irrigation via dynamic state variables calculated from moisture data.

To reach these goals, this study, thus, develops a methodology for the spatial extension of soil water regime variables using geomorphological indicators and high-frequency soil moisture data. This approach aims to create a geographically structured database that can quantify soil water dynamics in the top 20 centimetres across diverse terrain types, including both flat plains and hilly regions. By examining these distinct areas, this study can assess the variability of soil moisture and evaluate its applicability to broader regions. The findings from this research contribute valuable insights into drought and flood-related phenomena, potentially enhancing geographical decision support systems – such as precision agriculture tools – for optimal water resource management.

Materials and methods

The sample areas *(Figure 1)* are presented based on the relevant geographical feature for the research, which is land cover. The diversity of land cover in the areas of interest is significant.

The first sample area, the Cseres Valley, is in the watershed of the Kondó settlement's hilly terrain. The area is characterised by significant geological diversity, with its surface primarily composed of Mediterranean shal-

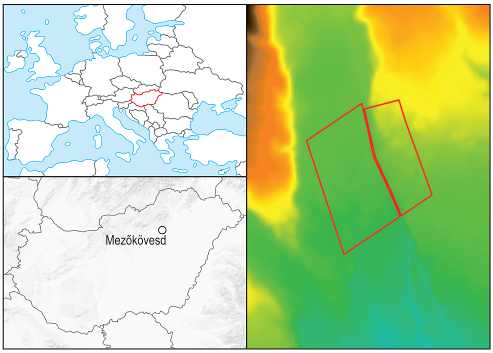

Fig. 1. Location of Mezőkövesd study area

low marine sediments that advanced during the Miocene Badenian and Carpathian epochs (approximately 17 million years ago) (Juhász, A. 1970). The geological landscape of the area exhibits considerable variability over geological epochs. During glaciations, degradation through frost weathering was prevalent, while in interglacial periods, increased precipitation caused linear erosion and weathering to be dominant factors (Pinczés, Z. *et al.* 1993; Harangi, Sz. 2001). Soil movements, both during glacial (cryoturbation, geliflucion) and interglacial periods (gelifluction, solifluction), shaped the surface. Sediment deposition occurred with varying efficiency during the Villányian, Biharian, and Pilisian stages (Dobos, A. 2002). The entire area of the Cseres Valley belongs to the Formation of Egyházasgerge (eMK), with gravel conglomerate found deep down, covered by sand, sandstone, and finer silt and clay on the surface (Gyalog, L. 1996).

The Cseres Valley is V-shaped, 1.6 km long, and 665 m wide, narrowing at the valley throat, with a watershed area of 0.76 km^2. The valley is incised into the terrain to depths of 4–5 metres in places. Several erosional gullies of varying degrees of development, caused by rainfall, accompany the valley, and since 2010, these have also been shaped by the periodic (from spring to autumn) flash floods (Vágó, J. 2012). The area falls within the forest soil zone. The soils identified so far are luvisols, stagnic luvisols, and gleysols. Their common characteristic is high compactness, which is attributed to land use. Most of the valley has been used primarily as pasture or orchards, with smaller forests found on steeper slopes and in the valleys. Cultivated fields and meadows are located on more suitable areas of the slopes, where the signs of machinery work (machine tracks) are evident and are also reflected in the structure of the soils.

Ancient maps suggest that land use has remained unchanged for several centuries. The distribution of soil types from higher elevations to lower ones is as follows: strongly eroded brown forest soil with levissage near the hilltops and watershed ridges, predominantly anthropogenic colluvial soil in the middle of the slope due to its local position, eroded and heavily compacted brown forest soils on the north- and south-facing slopes. At the valley bottom, repeatedly buried gleysoils deposited by cyclical flash floods in the valley, followed by deposited meadow soil rich in anthropogenic materials at the edge of the settlement zone (Dobai, A. and Dobos, E. 2023).

The studied area is moderately warm and moderately dry around 2050. The annual average temperature ranges from 8.8–9.3 °C. The average maximum temperatures on the hottest summer days range from 31–33 °C, while the average minimum temperatures on the coldest winter days are around -17 °C. Annual precipitation ranges from 550–600 mm. The predominant wind directions are NW and SE, corresponding to the terrain, with an average wind speed of 2.5 m/s (Péczely, Gy. 2006; Dövényi, Z. 2010).

In contrast to the previous area, the sample area located near the town of Mezőkövesd on the Bükk pediment exhibits somewhat greater diversity, with stronger manifestations of Luvic Chernozems and gleyic characteristics, previously traversed terraces (see *Figure 1*). The area consists of a mixture of material eroded from the Bükk Mountains and sediment from the Hór Stream. Corresponding to the topography, soil erosion is significant, with the thickness of the humus layer primarily determined by the extent of erosion.

Humus layers ranging from 30 to 80 cm in depth disappear on the slopes, giving way to heavily clayey parent rock. In extreme cases, erosion is halted by the omnipresent calcium carbonate accumulation layer, resulting in patches of calcareous soils.

The area is predominantly characterised by vertisols formed on highly expansive clayey alluvial sediments in the lower parts of the hills, exhibiting good water retention capacity but cracking to depths of 100–130 cm when dry, with cracks 3–7 cm wide. Surface organic matter is sporadically distributed throughout the profile. The filling of cracks leads to loss of free space, and upon rewetting, the expansive clay exerts strong pressure on soil structural elements, resulting in the formation of slickensides, even at depths of 50 cm. These processes result in heavily compacted soils. The high clay content is mitigated in the Hór Valley bottom areas, where loess, loamy material forms the upper 40–80 cm. Chernozem brown forest soils are found only in the southern corners, with the upper layers throughout the profile being formed by loess.

A significant portion of the studied area falls on the bottom of the Hór Valley, where we find alluvial soils mixed with gravel and tuff debris in areas where the Hór Stream previously meandered. In areas where the Hór formed smaller alluvial cones along abandoned channels, loess forms the upper layers of the soil. Strong water influence is not characteristic of the area. Due to the high clay content of Vertisols, signs of stagnant water are present throughout the profile, albeit not pronounced. The alluvial deposits in the valley bottoms, characterised by iron-humic dark colouring and iron and manganese spotting, also indicate water influence, although without a distinct meadow character. Groundwater influence is not observed. The regulated flow of the Hór quickly subsides below the reservoir when water reaches the lower section, with only surface runoff characteristic on the interfluves. Due to the high clay content, infiltration is relatively low. On the sloping hillside surfaces, water drains quickly. Although the process of steppe formation is underway, the soil water regime remains positive (Chernozem brown forest soils), thus, salt accumulation is not expected. Due to the previous loess cover, clays are enriched with basic cations, with calcium being the most characteristic, but magnesium content is also notably high among the basic cations typical of loess. Due to monocultural farming, the flora and fauna of the sample areas are monotonous, with some colour provided by the young, planted forests of the Kondó sample area. Their land use generally consists of abandoned or active arable land.

Monitoring methodology and data processing

The decision-making system starts and works with the entity of our soil monitoring system, the Sentek soil moisture sensors. The Sentek soil moisture sensors operate based on electrostatic interaction, using a capacitive method, where the volumetric water content is derived from the dielectric constants of soil, water, and air, with the unit of measure being volumetric percentage (%). The devices respond even with the smallest changes in moisture content because a relatively low amount of water has a high dielectric constant, significantly increasing the dielectric constant of the mixture of the three elements (water, air, soil) (Al-Ghobari, H.M. and El Marazky, M.S.A. 2013). The electrical capacitance can vary depending on the soil, specifically on the proportions of the three elements and their chemical properties. Therefore, calibration of the sensor is required before measurement, considering the physical properties of the soil, primarily its mechanical composition (Kibirige, D. and Dobos, E. 2021).

The data processing began with the soil moisture data time series collected by the Sentek soil moisture sensors. The purpose was to create a database compiled for each sensor, from which soil water regime variables could be calculated, well reflecting the periodic changes in soil moisture at twenty centimetres depth of the soil. Soil moisture measurements were taken between 2019 and 2022 in the pilot area, with at least one year's worth of temporal data available for each sensor with a two-hour temporal resolution for Mezőkövesd. Since the soil moisture data originates from a depth of 20 cm, evaporation is the most significant climatic factor that can be detected in the soil moisture fluctuations across different seasons *(Figure 2).* Generally, these values are opposite from season to season.

Due to the variability of these values, it is not possible to create new, universally applicable variables from the database created from the measured data. Therefore, examination periods like season combinations were designated to effectively characterize the evaporative conditions of the given period. On Mezőkövesd pilot area (149.74 hectars) two periods – spring-summer and autumn-winter seasons – were chosen. Altogether 13 sensors were available: 6 sensors in the spring-summer season, and 7 ones in the autumn-winter season.

With this period designation, a complex database was created that includes spatial and temporal filtering of the time series data measured in the sample areas, thus, establishing area-specific soil water regime variables. These variables characterize soil properties related to water at the measurement points (Stefanovits, P. 1999; Deák, T. *et al.* 2022), which were the following:

- Infiltration and drying rate (V/V% / time): Both rates are created from the time series of soil moisture measurements, where a new variable was created that contains the value differences between the soil moisture measurements. The new variable contains negative and positive difference values and was further filtered by taking the average value of positive and negative difference values separately. The average calculated from the negative values resulted in the drying rate, while the positive values resulted in the infiltration rate. Only the spring/summer dataset was used for the calculation of these rates as the value changes in the infiltration and drying periods are more present during these seasons and represent these variable conditions (see *Figure 2*).
- Total porosity (V/V%): This value represents the highest measured soil moisture value during the logging, where the thick and thin pores of the layer completely exclude air and get fully saturated with water. The autumn/winter dataset was used for the calculation because the lower temperature and evaporation conditions make the finding easier and more representative.
- Minimal water content (V/V%): This value represents the lowest measured soil mois-

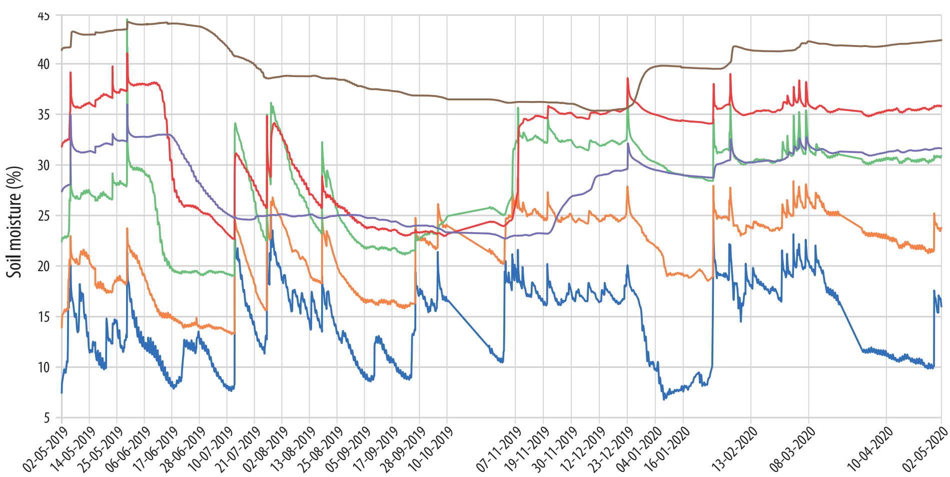

Fig. 2. Changes of soil moisture between 02.05.2019 and 02.05.2020 in Mezőkövesd. *Source*: Authors' compilation.

ture value during the logging. The spring/summer dataset was used because of the higher temperature and evaporation conditions in Hungary (Péczely, Gy. 2006; Dövényi, Z. 2010).

– Water holding capacity range (V/V%): This value was calculated by subtracting the minimal water content from the total porosity, which shows the range within which the soil moisture can change. In this case, the whole yearly time series dataset was used since none of the seasonal conditions affect this variable, and the most amount of data is needed to find the widest range of change in terms of soil moisture.

Since only point-wise target variables measured by the sensors within the sample areas are available, spatially independent auxiliary variables had to be employed to aid the extension and reduce statistical uncertainty (Bock, M. *et al.* 2007). Thus, 14 independent geomorphological variables (GVs) were defined created from digital elevation models of each sample area with a spatial resolution of 5 metres *(Table 1).*

The GVs created from the "Basic Terrain Analysis" module of a desktop-based geographic information system (GIS) were called SAGA-GIS (Conrad, O. *et al.* 2015). The spatial extension was performed using Regression Kriging, which is a methodology that utilizes spatial estimation, combining spatial correlation from Kriging with the pixel value estimation from many choosable regression models (Hengl, T. *et al.* 2007). In this case, for Kriging, the Ordinary Kriging and for a regression model, Random Forest (RF) were employed as the default methods, commonly used for spatial extension of environmental variables in geostatistics (Hengl, T. *et al.* 2018).

Table 1. List of available geomorphological variables (GVs)

Closed Depression	Profile Curvature
Convergence Index	Plan Curvature
Closed Depression	Relative Slope Position
Channel Network Base Level	Slope
Channel Network Distance	Total Catchment Area
Relative Relief	Topographical Wetness Index
LS-Factor	Valley Depth

The study involved analyzing sample areas with different geomorphological characteristics. Consequently, different GVs were always crucial for the spatial extension of a given variable. To determine this, only specific variables can be used due to the collinearity of the variables. Picking GVs required a set of rules, which were the following:

– The amount of GVs can't be more than the number of points (training data) used for the spatial extension due to the curse of dimensionality (Ying, X. 2019).

– The GVs need to have the lowest correlation between them hence the independence of these variables.

After setting these rules, a Pearson correlation analysis (Sedgwick, P. 2012) was used to determine a list of independent variables which will be used for the spatial extension of the water regime variables *(Figure 3).* The steps were the following:

1. The first independent GV was chosen based on how many other GVs had a correlation between 0.03 and -0.03. The one with the most variables that would fit this rule would be the first while the remainers were the ones that picked by the correlation threshold (0.03) inside what was available for the first GV.

2. In this case, the "Slope" GV had 4 variables, the greatest number of variables within the correlation threshold. The "Slope" variable was the first, while the remainers were the Convergence Index, Plan Curvature, Profile Curvature and the Relative Relief (see *Figure 3*). These remainers were inside the correlation threshold compared to the first, picked "Slope" GV.

3. If there are two or more cases where every variable had the number of variables, then it would be decided which had the lowest average correlation value. This was not the case in our correlation analysis, but this rule was brought up for replication.

The picked GVs are used in basic terrain analysis like slope and curvature types of the terrain with some more complex ones like the conver-

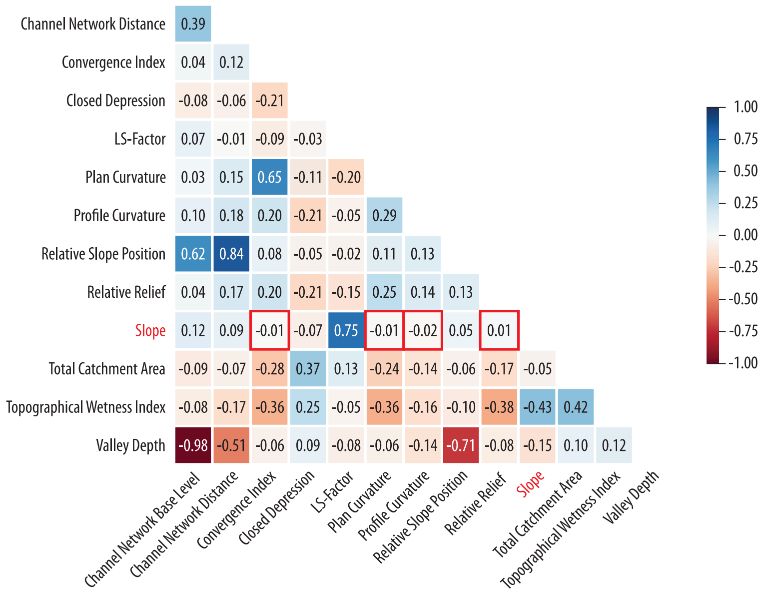

Fig. 3. Correlation matrix between the GVs derived from the DEM representing the Mezőkövesd pilot area and the picked independent variables highlighted with red borders and text. *Source*: Authors' compilation.

gence index, which shows the extent of either convergence or divergence by pixel (Kiss, R. 2004) and the relative relief, which was calculated by dividing the pixel values of the focal average from the digital elevation model.

Validation of the infiltration rate variable using on field infiltration measurements

During the data collection of soil moisture values via the Sentek sensors, on field infiltration experiments were done on Kondó, in the same sensor positions during the summer of 2022. These experiments aim to measure the infiltration rate with field tools so it can be used for validation and comparison to the infiltration rate variable made from the time series soil moisture readings.

This experiment extended to three Sentek positions *(Figure 4)* on field with constant head infiltration measurements. The main purpose of the method used is to measure the amount of water infiltrating into the soil per unit of time by placing two metal frames on the soil. The outer frame provides constant hydrostatic pressure to ensure that the water in the inner frame infiltrates deeper into the soil and does not escape laterally (Várallyay, Gy. and Fórizs, J. 1966).The measuring process involved fully saturating the area around the Sentek sensors with water and then gradually measuring how much water infiltrated over time for at least 2 hours. These measurements were then converted to the same temporal resolution as that of the Sentek sensors, resulting in one predicted soil moisture measurement in V/V% per two hours.

Implementing Leave-One-Out Cross-Validation for the spatial extension of water regime variables for validation

The model performance evaluation cannot be done by splitting the data due to the already low amount of points usable for spatial extension.

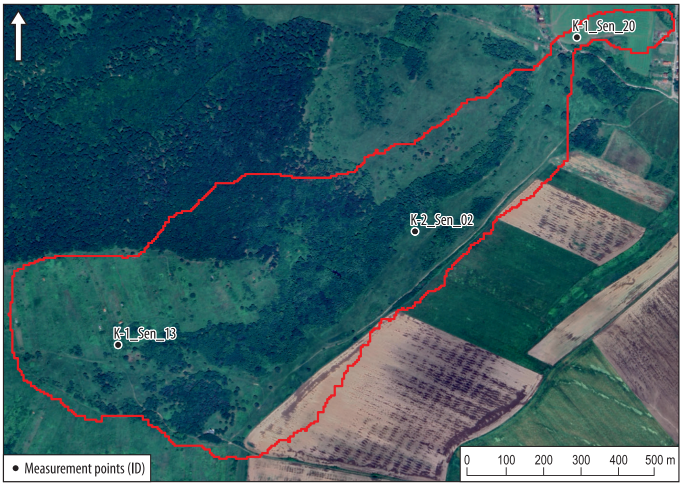

Fig. 4. Pilot area of Kondó featuring the sensor/field measurement points. *Source*: Authors' compilation.

A different validation methodology was needed, and Leave-One-Out Cross-Validation (LOOCV) was chosen for this reason (Berrar, D. 2019). This validation process requires the creation of several models and values from an evaluation metric of choice. The model creation happens by making as many iterations as many points are available. At each iteration, we create a model with one less point. This point is the test data, while the remainer points are the training data for that model iteration. Every iteration shows a different point taken out as a test point.

In this case, each water regime variable had six iterations *(Figure 5)* (except for total porosity with seven used from the autumn/winter dataset – *Figure 6*) of models with their own evaluation metric which was root mean square error (RMSE) in our case.

Results and discussion

Monitoring

While the spatial extension of each water regime variable used the same list of independent variables, depending on the iteration, the results were different.

Infiltration and drying rate

Both rate variables have their lowest RMSE values on the fourth iteration *(Table 2).* In terms of spatial extension, they are correlating with each other regarding how values are distributed around the pilot area. The best areas when it comes to drying and infiltration are located on the north-western side of the plot area, while the worst on the southern half with distinguishable, natural topographic features such as the side valley of the Hór stream bearing the lowest drying and infiltration values *(Figure 7).*

Due to the veiny, thinner look and spatial distribution of the pilot area, the convergence index could be the most related when predicting drying and infiltration rates for the area (see *Figure 7*).

Total porosity

For total porosity, it was the only variable with one more iteration plus compared to the others, resulting in the fourth iteration as the worst, which was the complete opposite of the rate variables (see *Table 2*). However, it only took one more iteration to be the best, resulting the

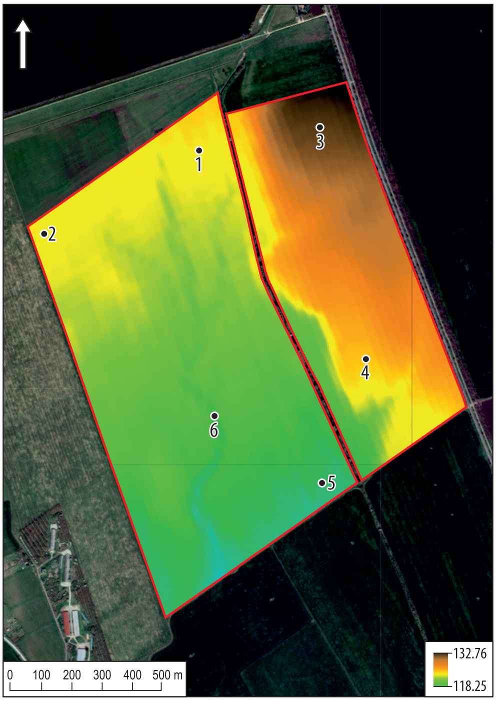

Fig. 5. Iteration order of the left out points (test data) for the spatial extension of all water regime variables (except total porosity). *Source*: Authors' compilation.

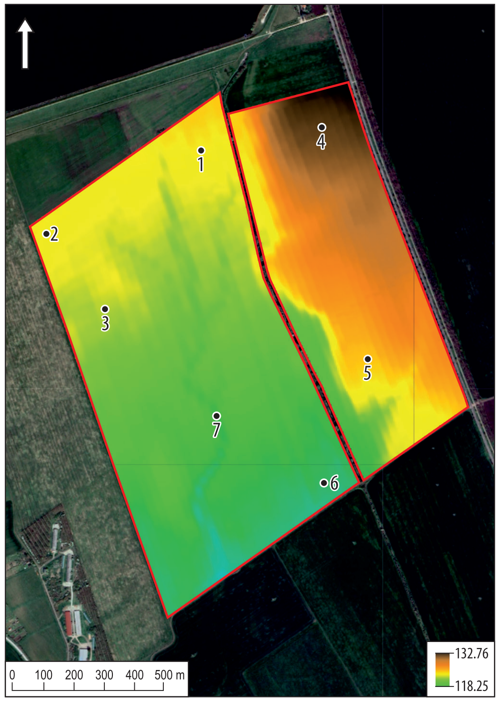

Fig. 6. Iteration order of the left out points (test data) for the spatial extension of total porosity. *Source:* Authors' compilation.

Table 2. RMSE values of each model iteration for every water regime variable

Iterations	Infiltration rate	Drying rate	Total porosity	Minimum water content	Water holding capacity
	V/V% / 2 hour		V/V%		
1	0.041799	0.022277	0.670538	4.074932	0.179433
2	0.044332	0.020514	0.855228	3.736326	0.013592
3	0.024276	0.016299	0.017738	3.620505	1.071288
4	0.000161	0.000605	1.582832	3.495494	0.011158
5	0.036959	0.017024	0.006760	2.856400	0.009271
6	0.030051	0.018315	0.007070	0.012209	0.006486
7	–	–	0.013099	–	–

lowest RMSE value in the fifth iteration. When it comes to the spatial distribution, there is a northern and southern split in terms of values.

However, the split is not as homogeneous. There is also a split between the artificially created valleys defined by the north-western sowing direction of the plot area (see *Figure 6*). By checking GVs that greatly distinguish micro valleys like the DEM and convergence index, it's obvious how the sowing direction changed the micro topology of the area while also highlighting holes in between them referring to the natural topological features like side stream valleys (see *Figure 7*).

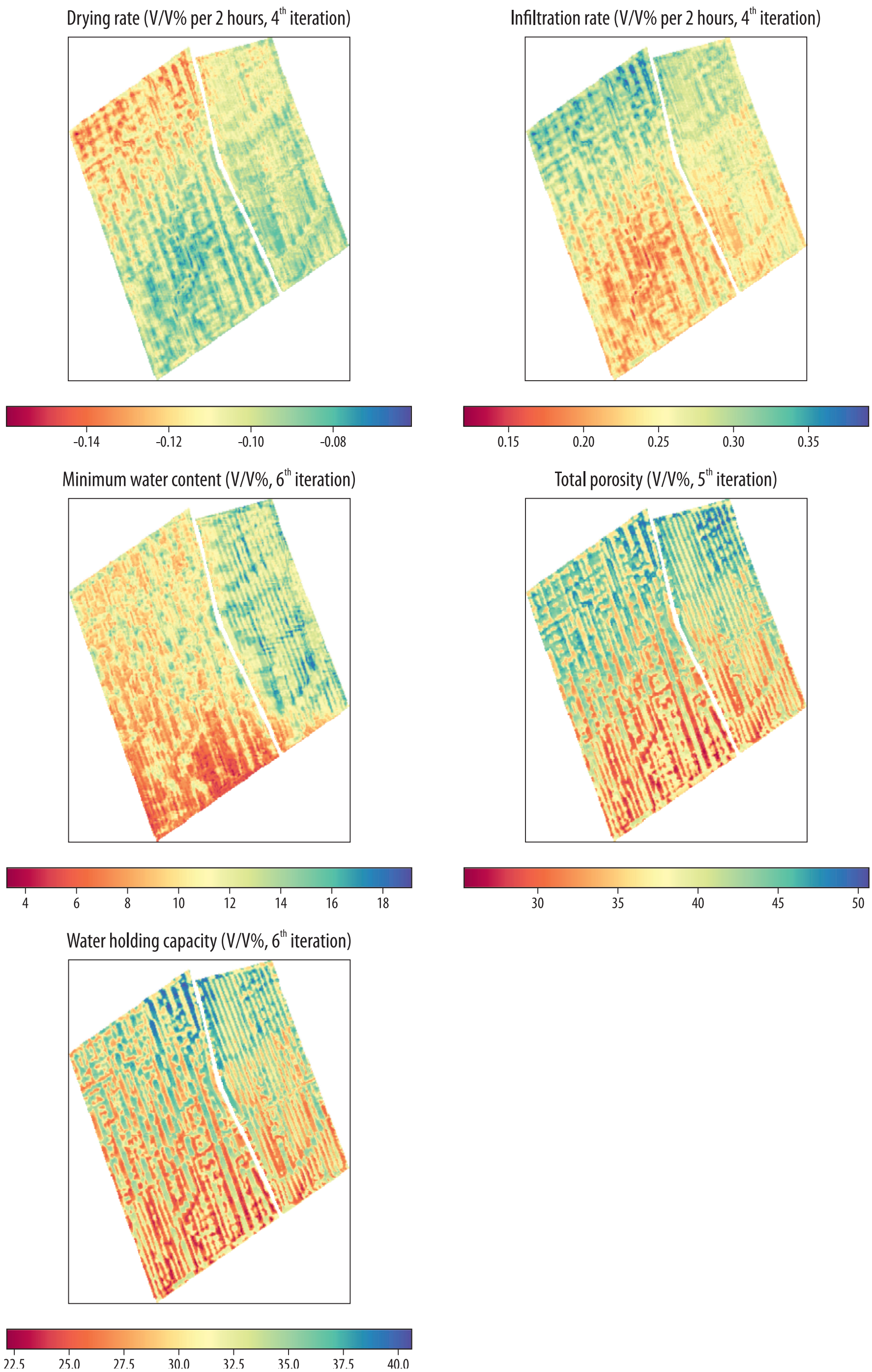

Fig. 7. Each water regime variable's best iteration of spatial extension in terms of RMSE value from the Mezőkövesd pilot area. *Source*: Authors' compilation.

Higher values can be found in lower micro valleys, where material convergence is intact, while lower values are on micro ridges throughout the whole plot area. Due to the presence of natural side valleys, these artificial valleys and ridges are not constant but separated in areas where a direction change happens along the surface. These areas are well represented by the slope and curvature GV's (see *Figure 7*).

Minimal water capacity

For minimal water capacity, the sixth iteration was the best regarding RMSE value (see *Table 2*). The spatial distribution is most homogenous compared to the other water regime variables, where there is an east and west value split (see *Figure 7*).

Highlighted lower and higher areas also can be spotted similarly to the total porosity which are side stream valleys. The value split might indicate significance to the elevation of the area, even though DEM was never used as an independent variable for the spatial extension.

However, the relative relief could be the most significant variable in this case as it only generalises the elevation and gives a buffer to the natural side alleys of the area, hence giving a rough look and distribution to those areas where the lowest and highest values are *(Figure 8).*

Water holding capacity range

Water holding capacity range uses the same sixth iteration as its best iteration (see *Table 2*) while also having an almost identical spatial distribution compared to total porosity.

The only real difference is in the artificial micro valleys with lower valued pixels, meaning there is a more significant value difference between artificial topographic features when it comes to the water holding capacity of the pilot area *(Figure 6).*

Validation

In our comparison, we had three sensors of data representing the 2022 spring/summer season, with all of them having in field infiltration measurements. While there were not a lot of sensors around the area which we could use, the results show that the differences can vary between 0 to 46 percent value difference when comparing the infiltration rate calculated from the time series data to the on-field measurements *(Table 3).*

This can be due to the different geomorphological circumstances or the methodology used to calculate each point of infiltration using the drying periods of the time series soil moisture measurements.

Discussion

The methodologies and results in this study contribute to advancing precision irrigation through three key perspectives: methodological, device, and spatial resolution. These enhancements aim to support data-driven irrigation decision-making in agricultural settings with improved accuracy and scalability.

Methodological perspective

One of the foundational principles of digital soil mapping is extending sampled soil properties using spatial interpolation methods, commonly relying on distance-based approaches such as Kriging (Lagacherie, P. *et al.* 2006). However, these methods often struggle when the microtopography highly influences the target variable (e.g., soil moisture) and re-

Table 3. RMSE values of each model iteration for every water regime variable

ID	Field measured	Sensor measured	Difference, %
	V/V% / 2 hour		
K-2_Sen_02	0.11	0.31	20
K-1_Sen_20	0.05	0.51	46
K-1_Sen_13	0.24	0.24	0

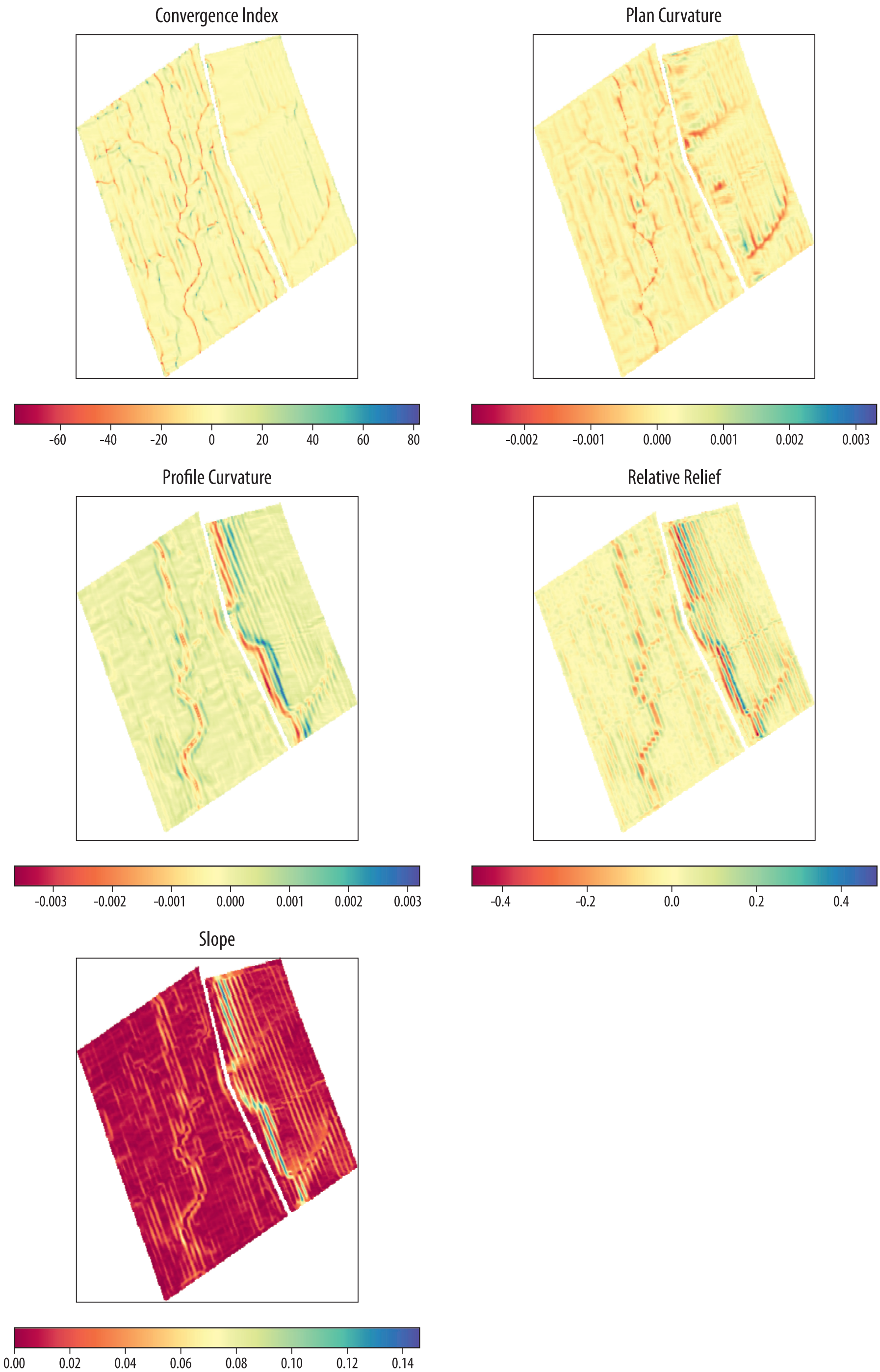

Fig. 8. All independent variables used for the spatial extension of the water regime variables from the Mezőkövesd pilot area. *Source*: Authors' compilation.

quires a high sampling density to capture local variations accurately. For soil moisture, which correlates closely with topographic features (Guo, X. *et al.* 2020; Winzeler, H.E. *et al.* 2022), a pure, distance-based, spatial interpolation approach may produce limited accuracy due to its inability to capture the nuances introduced by geomorphological complexity. This study employed a machine learning approach combined with multiple geomorphological descriptors derived from a 5-metre high-resolution digital elevation model (DEM). By integrating terrain variables with soil moisture data, we created spatially extended variables that reflect not only spatial proximity but also distance in value, accounting for the influence of topographic variability, which is the whole point of using Regression Kriging for spatial extensions (Hengl, T. *et al.* 2007). This hybrid approach enables a more nuanced spatial dataset that captures both spatial transitions and topographic-driven variations in soil moisture and water management variables.

Comparable studies have demonstrated similar benefits of integrating terrain models for soil property mapping (Li, X. *et al.* 2020; Adeniyi, O.D. *et al.* 2024). Still, such methods have been limited mainly to soil physical and chemical attributes while relying on Regression Kriging. Our approach, thus, represents an adaptation of these techniques to soil moisture, extending their applicability to soil water regime variables within high-resolution, localised with agricultural contexts.

Device perspective

Precision irrigation has increasingly adopted tools and methods that align with plant-specific water requirements, with tensiometers being among the most widely used devices to measure soil moisture in response to plants' water needs. Although effective, reliance on tensiometers or similar tension-based devices constrains soil moisture monitoring systems that support precision irrigation (Owino, L. and Söffker, D. 2022). Many existing systems made for these tensiometers are incompatible, creating a gap in expanding irrigation support capabilities using a broader range of affordable, other than the tensiometer, volume-based soil moisture sensors (Abdelmoneim, A.A. *et al.* 2023). The issue isn't that other devices can't be used; rather, compared to water tension methods, there are currently too few effective and scalable alternative methodologies that provide spatial data-based support for precision irrigation without relying on tension meter devices. Our study overcomes this limitation by demonstrating that time-series soil moisture data measured in volume percentage (e.g., using Sentek EnviroSCAN dielectric sensors) can provide comparable insights into soil water regimes.

The methodology developed here enables measurements from dielectric constant-based devices, regardless of depth or logging frequency, to be seamlessly integrated into irrigation support systems. This flexibility significantly broadens the range of feasible soil monitoring setups, from cost-effective 10 cm depth sensors to high-frequency logging, multi-depth, industrial-grade sensors. The adaptability provided here to scale measurements across device types presents an economically viable solution for stakeholders aiming to implement or expand soil monitoring systems within precision irrigation management.

Spatial resolution perspective

Many research, commercial, and governmental entities currently rely on freely available optical remote sensing data for monitoring soil moisture on a broad scale (Joshi, N. *et al.* 2016). While this data is useful for national and regional assessments, its spatial resolution is typically inadequate for precision irrigation at the farm or field level (Dobos, E. *et al.* 2013). Moreover, freely available optical, remote sensing data is generally disconnected from localised topographic influences, which are critical for effective moisture management in undulating or heterogeneous landscapes (Wang, S. *et al.* 2018). Our research addressed this limitation by using high-resolution DEM generated from RTK GPS-measured point clouds with a spatial resolution of 5 metres. From this DEM, we derived GVs – such as elevation, slope, curvature, and other terrain variables – that are essential in characterizing and predicting soil moisture variability at the sub-field level. This resolution enables us to capture and quantify subtle relief factors that influence soil moisture dynamics, providing a more accurate basis for precision irrigation planning. By linking these topographic variables to in situ soil moisture and water management measurements, we created a spatially refined dataset that supports precision agriculture by connecting soil moisture information to local field terrain conditions.

Conclusions

The micro-topographic properties are appropriately reflected in the resulting maps. The elevation model shows that a higher sloped region and former streambeds fundamentally characterize the area. Accordingly, the texture of the soils in the area is varied. On the higher terrain, the soils are clayier, while in the lower areas, they consist of thin sand, sandy loam, and gravelly material from the former streambed. These properties can be quantified by the various geomorphological variables (GV), and these surface characteristics are highlighted. The total porosity map confirms the previously mentioned features and these observations can be further analysed and evaluated on the infiltration, drying, and minimum water content maps. Excluding the water holding capacity dataset results, which may differ in this case, considerations must also be given to field sampling experiences and variability arising from previous datasets.

The relationship between hydrological datasets and GVs entails uncovering the most characteristic and extreme micro-topographic areas within the pilot area first due to factors such as the sensor installation location and the land use. Data collection must be performed on these points (whether for soil sampling or deploying smart devices such as Sentek soil moisture sensors), which can be more challenging in monocultural agricultural fields, where artificial microtopographic features must be considered.

Further improvement in estimation accuracy can be achieved by collecting data at intermediate points within known topographic features, not just at the most extreme endpoints. For example, if it's found during field research that directional changes or other geomorphological features (such as terraces) are present along uniform slopes, it's worthwhile to collect data not only at the lowest and highest points of the slope but also from the in between topographic elements.

The importance of placing these sensors can also be backed up with the iteration order of the spatial extension. Either the first or the second was the worst iteration for almost every water regime variable (see *Table 2*). In real life, these iterations belonged to points which were placed on heights which were in between the lowest and highest heights (see *Figure 7*). This indicates that there is a risk of error if the points are not placed evenly on geomorphological features, be it either natural or artificial (Chen, Y. *et al.* 2021).

The preliminary validation results show that more on field measurements are required at sensor points to have a better understanding of how robust the methodology when creating the infiltration and drying rates just based on time series soil moisture measurements done by the Sentek sensors. Validation of the other water regime variables is also a future goal for this ongoing research, which can be expanded by collecting soil samples and comparing soil physical parameters that can be used and correlated to validate these variables.

Looking at the list of independent variables, the picked variables correlate to the artificial topographic features located in an agriculturally heavily used area. Slope and curvature types clearly represent the constant direction changes of the landscape. While the 5-metre spatial resolution was not enough to clearly spot it, new, significant, artificially created micro valleys are being developed over time, which can be detected in the convergence index (see *Figure 8*). These micro valleys also contribute to the poor water circulation which clearly shows the predicted water capacity range and total porosity maps (see *Figure 7*). This is due to the constant, intensive agriculture.

Overall it can be concluded that the methodology can provide a suitable foundation for the initial determination of soil water regime characteristics, thereby aiding in precision agriculture and irrigation development. Future research directions will aim to incorporate additional sample areas, densify field training and test points, and further strengthen the current results.

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The effect of different water types commonly applied during laser diffraction measurement on the particle size distribution of soils

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Abstract

It is expected in the future that soil particle size distribution (PSD) measurements by laser diffraction method (LDM) may replace sieve-pipette sedimentation methods (SPM) as they are faster, require less sample, and are accurate and reproducible. LDM measurement result is a continuous function of PSD, which can facilitate the conversion between the various limits (by countries, by scientific field) of the calculated particle size fractions (PSF – e.g. clay, silt, sand). Currently, there is no standard method for LDM PSD measurement. Many different types of instruments and preparation devices are currently used in laboratories, with various sample preparation, pre-treatment and measurement methods (duration, chemical and/or mechanical dispersion, settings, etc.). In soil LDM PSD measurements, researchers put relatively little emphasis on the choice of the type of aqueous media used. Thus, it is still questionable to what extent the results of the LDM measurement depend on the selection of the dispersion method and the aqueous media. For our research, eight soil samples with various physical and chemical properties were collected in Hungary. The particle size fractions (clay, silt, sand) determined with LDM (Malvern Mastersizer 3000) measured in three types of aqueous media (distilled, deionized and tap water), in different combinations of two dispersion methods (no treatment, ultrasonic or chemical dispersion with Calgon and their combination) were compared. For the comparison, PSF results of the conventional sieve pipette method (SPM) were used as a reference. Our results showed that LDM measurement can achieve various degrees of dispersion with different preparations, in many cases only partial dispersion, disaggregation, sometimes re-aggregation, and flocculation of soil particles were observed as compared to full preparation (in SPM). The "disaggregation pattern" of the soil samples also depended on the quality of the aqueous media and the properties of the soil investigated, because several types and degrees of interactions could occur in the various soil-liquid-dispersant/disaggregation effect systems.

Keywords: pre-treatment, ultrasound, soil texture classification, aqueous media

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Introduction

The particle size distribution (PSD) of soils can be considered one of the most important properties of soils. It may influence many other soil properties (e.g. texture, structure, porosity, ion, molecule adsorption/desorption and nutrient cycling, microbiological activity, hydrological properties, etc.) and is also an important diagnostic criterion in soil classification.

Determining the PSD is an important research field in various industrial applications (pharmacy, ceramic industry, etc.) and also for the earth and environmental sciences (Blott, S.J. and Pye, K. 2008; Varga Gy. *et al.* 2019; Gresina, F. 2020; Polakowski, C. *et al.* 2023).

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Many methods are used by various fields of soil science and a wide range of related sciences for the determination of PSD (such as, for example, sieve-pipette method, aerometer method, PARIO or dynamic image analysis in geography, geochemistry, soil mechanics, hydrology (Gee, G.W. and Bauder, J.W. 1986; Miller, M.P. *et al.* 1988; Allen, T.A. 1990; Clifton, J. *et al.* 1999; Loveland, P.J. and Whalley, W.R. 2001; Nemes, A. *et al.* 2002). These methods differ in that they propose various sample preparation and pre-treatment steps (e.g. removal of organic matter, possibly carbonates and sesquioxides; applying ultrasound and/or dispersing agents) while using different instruments, measurement procedures. The so-called sedimentation methods (e.g. pipette and hydrometer methods) commonly require a lot of manual labour. To eliminate the human error factor and for automation, various instrumental measurement techniques such as the laser diffraction method (LDM) or particle counting, optical sensing were developed at the end of last century (Syvitski, J.P.M. 1991). LDM is now increasingly used to determine the PSD of soils (Pye, K. and Blott, S.J. 2004; Kovács, J. 2008; Ryżak, M. and Bieganowski, A. 2011; Sochan, A. *et al.* 2012; Yang, X. *et al.* 2015).

The advantage of LDM is that it is fast (3–10 min/sample on average), accurate and provides high reproducible measurement results. It gives the result as a continuous function compared to sedimentation methods (e.g. sieve-pipette, hydrometer) (e.g. Konert, M. and Vandenberghe, J. 1997; Buurman, P. *et al.* 2001; Gresina, F. 2020; Igaz, D. *et al*. 2020). However, we do not yet have sufficient experience in comparability and convertibility of the results obtained with various commonly used sedimentation and LDM measurement methods (Ryżak, M. and Bieganowski, A. 2011; Makó, A. *et al.* 2019; Svensson, D.N. *et al.* 2022).

The currently known major drawback of LDM is that it is limited in its ability to take into account the irregular shape or various optical parameters of sediment or soil particles, which may affect LDM results (Varga, Gy. *et al.* 2015; Bieganowski, A. *et al.* 2018; Varga, Gy. *et al.* 2022). The disadvantage is also that it cannot distinguish between the light diffraction of elementary particles and soil aggregates. This is the basis, for example, for LDM measurements of soil aggregate size distribution (ASD), mainly without pre-treatment (e.g. Kubínová, R. *et al.* 2021; Polakowski, C. *et al.* 2021a). Furthermore, the stability of aggregates can also be determined by LDM methods from the ratio of these size fractions or its changes during treatment with time (with the amount of disaggregation effects/forces (by dispersants and/or ultrasound – e.g. Rengasamy, P. *et al.* 1984; Field, D.J. and Minasny, B. 1999; Mason, A. *et al.* 2011), with applying fluids with various polarity (e.g. Mamedov, A.I. *et al.* 2007) or other statistical indices calculated based on the change of PSD curves (Bieganowski, A. *et al.* 2018).

According to the literature, deviations might be observed between results of various LDM PSD measurements. The results of LDM can be influenced by a number of factors. These can be grouped into several large categories: method of sample pre-treatment and preparation; the type of device used; the type of optical model chosen; the operation of the data processing software; operator-dependent settings; the suitability of the sample to be examined in terms of LDM (Makó, A. *et al.* 2017a; Bieganowski, A. *et al.* 2018; Varga, Gy. *et al.* 2019).

Based on a summary of Bieganowski, A. *et al.* (2018) on earth and soil science literature, preparations (removal of binding agents, such as organic matter, lime, iron oxides) or pre-treatments, chemical (adding NaHMP, Calgon, alkaline salts etc.) or physical dispersion methods (slaking or only stirring and circulation and/or use of ultrasound of different intensities) all influence the accuracy and repeatability of the measurement. In practice, the preparation methods traditionally used in sedimentation measurements (total or partial removal of adhesive materials) are omitted or inconsistently used in LDM PSD measurements due to their lengthy nature. It is assumed that disaggregation of soil samples also occurs during physical and/or chemical dispersion (e.g. Bartminski, P. *et al.* 2011). Ultrasonic dispersion, as a mechanical dispersion method, is widely used for LDM to achieve aggregate disintegration without damaging the primary particles (Raine, S.R and So, H.B. 1994). In most cases, mechanical and chemical dispersion are used simultaneously in LDM PSD measurements (Buurman, P. *et al.* 1997; Chappel, A. 1998; Ryżak, M. and Bieganowski, A. 2011; Virto, I. *et al.* 2011; Madarász, B. *et al.* 2012; Makó. A. *et al.* 2019; Polakowski, C. *et al.* 2023).

Some literature concerning ASD and aggregate stability measurement with LDM (or other methods) shows that the effect of soil properties on aggregate stability is complex, the resistance of soil samples to disaggregation effects may also differ in PSD measurements. Various effects of different soil properties can be dominant in the formation of aggregates, thus, also in the dispersion and disaggregation of soil samples if the investigated soils are rich in organic matter (e.g. Tyugai, Z. *et al.* 2010; Virto, I. *et al.* 2011; Schulte, P. *et al.* 2016), or has high carbonate (e.g. Virto, I. *et al.* 2011), Fe/Al-(oxi)-hydroxide (Zhao, J. *et al.* 2017), gypsum content (e.g. Pearson, M.J. *et al.* 2015), are hard clay soils (Rengasamy, P. *et al.* 1984) or soils of arid, semiarid regions (e.g. Amézketa, E. *et al.* 2003; Shein, E.V. *et al.* 2013; Goosens, D. *et al.* 2014). Since soils are very heterogeneous and complex materials, we do not have sufficient knowledge on how certain pre-treatments can affect the results of LDM PSD measurement with a specific combination of chemical and physical properties.

A simple parameter, such as the quality of aqueous media used in the measurement, may have an impact on the results. Dispersing media with different ion compositions can be used to examine, for example, the effect of the quality of irrigation water on the aggregate stability of dispersive soils and/or soil with high Na^+ and total salt content soils (e.g. Amézketa, E. *et al.* 2003; Almajmaie, A. *et al.* 2017). Manufacturers of laser diffractometers (e.g. Beckman-Coulter, Bettersizer, Fritsch, Horiba, Malvern) provide various general recommendations regarding the choice of water type for LDM measurements. Malvern, for example, does not recommend connecting a laser diffractometer to a tap water network because the high pressure of water and the sudden temperature change can cause bubbles to form, which the instrument can identify as particles during measurement (Malvern User's Manual). According to the Fritsch laser diffractometer manual, "normal" tap water is perfectly suitable for general purpose measurements (no mention is made of water chemistry or mechanical purity parameters), but it already points out that in some cases, it may be necessary to use distilled water (depending on the properties of the samples to be tested) (Fritsch User's Manual). No manufacturer provides specific recommendations on the water quality required for testing soil samples.

Several LDM experiments published in the literature have used distilled or deionized water to determine the PSD of soils (Ryżak, M. and Bieganowski, A. 2011; Sochan, A. *et al.* 2012; Kovács, J. *et al*. 2013; Varga, Gy. *et al.* 2016). However, there are also numerous publications in which authors have used tap water for their LDM PSD measurements in the case of sandy samples (Chappell, A. 1998; Storti, F. and Balsamo, F. 2010; Messing, I. *et al.* 2024) or heterogeneous textured soil or sediment samples (Ferro, V. and Mirabile, S. 2009; Özer, M. and Orhan, M. 2015; Abdulkarim, M. *et al.* 2021; Parent, E.J. *et al*. 2021). However, it is still questionable how the results of LDM PSD measurements can be affected by the chemical and physical properties of the soil samples, the types of pre-treatment, their combinations and the properties of the aqueous media used, and how these interact with each other.

Thus, the purpose of our research was to investigate to what extent influence the method of dispersion (chemical dispersion with Calgon or mechanical dispersion by ultrasound) and the quality of the chosen aqueous media (distilled, deionized and tap water) the clay/silt/sand contents of soil samples with different physical, chemical and mineralogical characteristics, calculated from LDM PSD measurements.

Materials and methods

Soil samples were collected from eight sites in Hungary (*Figure 1, Table 1).* The samples differed in their physical, chemical and mineralogical properties and were representative of the genetic horizons of the most characteristic Hungarian soil types.

Sample 1 (S1) and 8 (S8) contained predominantly smectite-type swelling clay minerals with high adsorption capacity. Sample 6 (S6) had high goethite content (10%) and their swelling clay content is dominated by vermiculite.

Samples 2 (S2), 3 (S3), 4 (S4), 5 (S5) were characterized by chlorite/vermiculite intercalation; they had lower adsorption capacity. Soil sample 7 (S7) contained few swelling clay minerals (dominated by illite and chlorite) and had the highest calcite content (10%).

Basic soil properties were measured according to the appropriate Hungarian standards (see detailed in Barna, Gy. *et al.* 2015). Macro-aggregate stability (WSA) was determined with an Eijkelkamp wet sieving device (Kemper, W.D. and Rosenau, R.C. 1986). LDM measurements were conducted on air-dried soil samples, that were sieved (< 2 mm) and cleaned from macroscopic plant debris (Barna, Gy. *et al.* 2015). Since in practice, in most cases, the removal of binding agents (carbonates, organic matter, and/or Fe-hidroxides/oxyhidroxides that hold aggregates together) was neglected, or inconsistently applied, typically for the purpose of "speed advantage" of LDM PSD measurement, we conducted our measurements without this kind of preparation steps.

LDM PSD determination was performed by Malvern Mastersizer 3000 device with Hydro LV dispersion unit. The effects of the type of aqueous media and treatments on the clay, silt and sand content of soils with various chemical and physical properties were investigated in matrix type treatment combinations using the method of Makó, A. *et al.* (2017b) and Polakowski, C. *et al.* (2021b). Distilled water (DW), high purity commercially available deionized water (DIW) or tap water (TW) was used as aqueous media *(Table 2).* Four types of physical and/or chemical dispersion were applied as pre-treatment: no treatment (T1); Calgon only (T2) or ultrasound only (T3) and their combination (T4). The Calgon solution was prepared according to ISO 11277:2009(E)

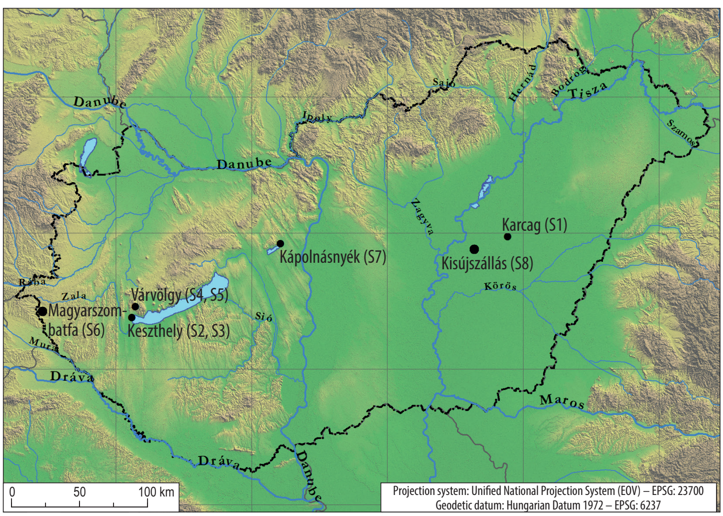

Fig. 1. Geographical positon of the eight sample sites (S1–S8) with the name of nearest settlement.

Table 1. Important physical and chemical characteristics of the soils included in the study

Sample code	WRB soil classification	Symbol and depth of genetic horizons, cm	Clay + Fe-oxihydrates, % (< 0.002 mm)	Silt, % (0.002–0.05 mm)	Sand, % (> 0.05 mm)	SOM,%	$CaCO_3$, %	CEC, mgEq/100 g	Exchangeable Na^+, mgEq/100 g	Water stable aggregates, WSA %
			SPM PSD,* solid part of the soil (100%)							
Sample sites **S1–S8**: see *Figure 1*										
S1	Vertic Stagnic Solonetz (Clayic) *Karcag***	**B** 5–30	51.09	45.90	0.88	2.00	0.13	40.85	20.63	20.84
S2	Hortic Terric Cambisol (Dystric, Siltic) *Keszthely***	**A** 0–30	21.09	33.13	44.28	1.45	0.05	11.84	0.14	53.40
S3	Hortic Terric Cambisol ** (Dystric, Siltic) *Keszthely*	**B** 30–50	22.90	33.87	42.29	0.93	0.00	12.38	0.13	38.47
S4	Cutanic Luvisol (Siltic) *Várvölgy***	**A** 0–20	15.27	29.35	54.05	1.33	0.00	10.36	0.12	87.57
S5	Cutanic Luvisol (Siltic) *Várvölgy***	**B** 20–50	22.30	26.56	50.49	0.65	0.00	12.78	0.15	38.38
S6	Vertic Gleyic Luvisol (Manganiferric, Siltic) *Magyarszombatfa***	**B** 20–50	38.96	25.93	34.61	0.49	0.00	16.78	0.17	44.41
S7	Vermic Calcic Chernozem (Anthric, Siltic) *Kápolnásnyék***	**A** 0–30	27.60	51.68	7.50	3.70	9.52	30.25	0.25	64.56
S8	Gleyic Vertisol (Clayic) *Kisújszállás***	**A** 0–30	53.88	41.19	1.05	3.89	0.00	35.69	0.29	59.14

*SPM PSD: Particle size distribution measured according to the conventional standardized sieve-pipette method ISO 11277: 2009 (E). ** The name of the *nearest settlement*.

(mixture of 33 g of Na-hexametaphosphate and 7 g of anhydrous Na-carbonate L^{-1}). Based on our own previous experience, the pumping and stirring speed during the measurements was 2750 rpm (Makó, A. *et al.* 2022). Prior to all the measurements, the system was degassed. The mass of soil samples added to the dispersing unit varied between 0.5 and 1 g, with obscuration ranging between 5 and 20 per cent. In T2 and T4, 2 cm^3 of Calgon solution was added as a dispersant to the air-dried samples on a watch glass, mixed gently with a glass rod, washed into the dispersion unit without residue, than another 25 cm^3 of Calgon solution was added to the soil suspension in the dispersion unit. The ultrasound was operated at maximum (100%) power, which was 40 W (frequency: 40 kHz), in the T3 and the T4. The ultrasound time was 240 seconds. During the measurements, the tank was operating with 100 percent volumetric efficiency (V = 600 cm^3) based on the level sensor setting.

The PSD of each soil sample was determined in three sample repetitions and in 3–5 replicates per sample. The light scattering data measured by the detectors were converted with Malvern software into PSD results based on the Mie theory. During the measurement, the following optical settings were used: absorption index (AI) = 0.1; solid phase refractive index (RI) = 1.52; and water refractive index (RI) = 1.33. Particle size fractions (PSF) were determined from the results

Table 2. Properties of the aqueous environments used during LDM measurement

Aqueous medium	pH	EC, µS/cm	Na^+	K+	Ca^{2+}	Mg^{2+}	Total hardness, mg/l CaO
			ppm				
Distilled water	6.4	2.2	0	0	0	0	0
Deionized water	6.1	1.5	0	0	0	0	0
Tap water	7.7	530.0	26	2.6	67	17	136

of PSD functions. The size limits 7 µm and 50 µm were applied as thresholds between clay-silt and silt-sand fractions based on the results of previous research by Makó, A. *et al.* (2019). The PSD of the soil samples had previously been determined by the conventional SPM sedimentation method according to the international standard (all adhesives removed) (ISO 11277:2009(E)) (see *Table 1*).

Statistical methods

Univariate (GLM/UNIANOVA) and One-Way ANOVA (Post-Hoc/Duncan test or Tamhane's test depending on the homogeneity of variances) were performed to examine the combined effect of the factors studied (pre-treatments, quality of the aqueous media) on the LDM measured particle size fractions (PSF – clay, silt and sand content) using SPSS ver. 20.0 software.

First, the amount of each particle size fraction (the results measured on all soil samples considered as a common group) per pre-treatment and per fluid were compared. The results were plotted on boxplot charts, in which the PSF values determined by conventional sieve-pipette measurements (SPM) were also displayed. As an additional step, we also examined how these effects were expressed in PSFs of soils with various physical and chemical properties. For visual and basic statistical comparison of PSF results were also displayed on boxplot diagrams and in tables per soil samples and per treatment (the former also included PSF values determined by SPM). Thus, our results might provide information not only on the effect of different types of treatments on the amount of clay (< 7 µm), silt (7–50 µm) and sand (> 50 µm) fractions in each sample but also the influence of the quality of the liquid phase used, the various types of preparation and the measurement methods used, respectively.

Results

Effects of treatments and the types of liquid media on the PSFs (clay, sand and silt content) of all the soil samples

The significant effect of the factors (pre-treatments, aqueous media quality, soil variation) and their combinations ($P < 0.001$ in all cases) on the measured clay, silt and sand content was proven by the results of GLM Univariate Analysis (UNIANOVA).

Comparisons using One-Way ANOVA tests showed that, for all three aqueous media, T1 resulted the significantly lowest clay content in all soil samples. If DW and DIW were used, the clay contents were not significantly different for T2 to T4, while for TW, T4 resulted in significantly the highest clay content *(Figure 2).*

Deviations in the quality of the aqueous media caused much larger differences in silt content. In the case of measurements in DW medium, the same trends as for clay content were observed: significantly lower silt content was measured in T1 than in T2-T4, but no verifiable differences between the results of T2-T4 were observed. For DIW, T1 resulted the lowest silt content, but the highest verifiable silt contents were obtained in T2. However, the highest amount of silt fraction in the TW was measured when the samples were treated with US and Calgon (T3).

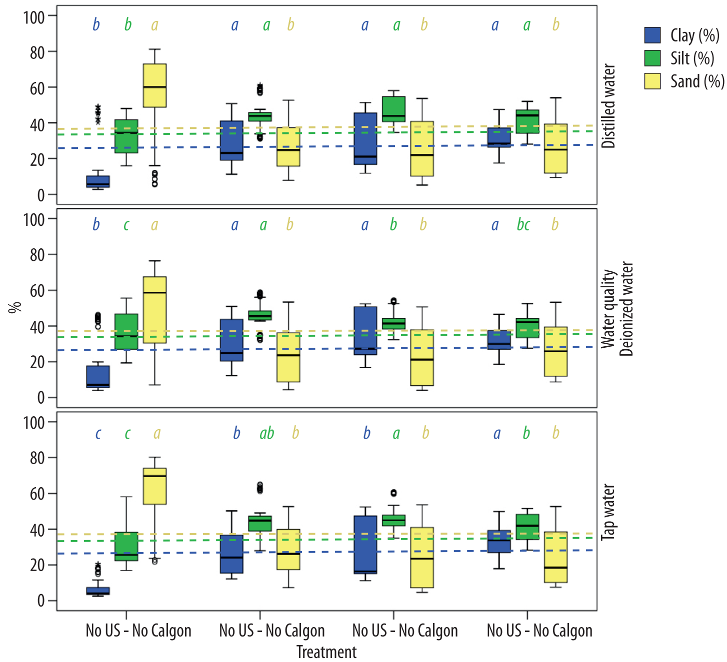

Fig. 2. Changes in LDM clay content in different treatments and aqueous media (all soil samples considered together). Means denoted the same letter did not significantly differ at $p < 0.05$ (One-way ANOVA). The dashed colour lines indicate the median values of SPM PSD results of the samples. *Source*: Elaborated by the authors.

For sand contents, a similar trend was experienced in all three aqueous media: the amount of particles in the sand fraction was significantly highest in T1, while no difference was experienced between the sand contents of the other treatments.

It is also worth comparing the first and third quartile values (Q1, Q3), the minimum and maximum values and the outliers in the boxplot diagrams in these figures. In *Figure 2*, the outliers showed the clay content of the high sodium content soil samples (S1), which were also dispersed by T1. Otherwise, it could be seen that the distances between Q1 and Q3 were narrow for all three aqueous media for T1, indicating that relatively little amount of clay was released from the aggregates.

In T2 and T3, the clay contents, in addition to being larger, were in a wide range (large interquartile ranges between Q1 and Q3). The clay content measured in T4 is, if not always significant, was the more and the interquartile range between Q1 and Q3 similarly narrow.

When examining the boxplot diagrams of the silt contents, the first striking feature was the larger variance of measurement results for T1, than other treatments. Outliers were observed for T2 and in some cases for T3, and then they disappeared in T4. Samples containing an outlier sand fraction could be mainly distinguished only from untreated samples if distilled water was applied.

There was no significant difference between the PSF values determined with DW, DIW or TW, but the boxplot diagrams showed that the quality of the aqueous media might have affected the results of the measurement. Without pretreatment (T1), for example, the standard deviation of the PSFs measured in deionised water was the largest for all three. In addition, the number of outliers and their values relative to the minimum and maximum PSF values were different.

Effects of preparation and measurement type on PSFs of all the soil samples

Using LDM, lower clay content, with enormous standard deviation was determined than with sieve-pipette method after total preparation of samples (SPM) (see *Figure 2).* There were exceptions to this: the LDM median values of clay content measured with T4 in DW, T2 and T3 in DIW were almost equal to the SPM median values, while in DIW and TW the T4 LDM measured higher clay contents than SPM. A similar or higher silt fraction was measured using the LDM method. A higher sand fraction of LDM than SPM measurement was experienced only in the case of T1 treatment.

Results of LDM analysis for soils with different properties

The dispersing effect of aqueous media for each treatment was displayed in four figures, where signs of One Way ANOVA ("a"–"c") presented the significant difference between mean PSF per various types of aqueous media (in abc order the mean values decreased). These figures provide the opportunity to visually investigate the effect of the quality of the liquid media.

Three tables contain the results of One Way ANOVA tests, where the effect of the treatments in various aqueous media was compared for each soil. In these tables, soils with the same dispersion patterns (showing similar levels of disaggregation response to various treatments) were marked with similar colours. First, we investigated the PSF determined by the LDM PSD measurement results of the samples with the highest clay content (S1: Karcag [*Solonetz*], and S8: Kisújszállás [*Vertisol*]) *(Figure 3).* In general, there was a significant deviation between the dispersibility of S1 and S8 soil samples in each aqueous medium. The clay content and CEC values of the two samples were very high (52–56% – measured according to the ISO standard; CEC: 40.85 and 35.69 mgEq/100 g soil – see *Table 1*), but only S1 had a higher adsorbed Na^+ content compared to S8 soil (20.63 and 0.29 Na^+ mgEq/100 g soil).

Rapid spontaneous dispersion of S1 samples was observed in T1 (stirring and flowing only) in DW and DIW water (due to the inherent sodium content of the samples), whereas this phenomenon did not occur in TW. (The clay contents measured in TW were significantly lower, and the sand contents were higher.) The repeatability of the measurement was also reduced at T1 in the case of all liquid media applied.

In the combined case (T4), we measured higher silt content and lower clay content than in any other treatment, apparently irrespective of the type of aqueous media. This phenomenon was not observed in the case of other soils.

The S8 sample contained very small amounts of adsorbed Na^+, and therefore, when it was placed alone in any aqueous media without ultrasonic treatment or addition of Calgon solution, the aggregates did not disperse significantly. The particle size fractions of S8 sample in the various aqueous media for each treatment were different (see *Figure 3*). In the case of samples treated without Calgon (T1 and T3), measurements in DIW media showed the highest dispersing effect (significantly the highest clay content was observed here). Either no significant deviations in dispersion were observed in the presence of Calgon (T2) or the results of measurement in TW showed the significantly highest clay release (T4). The difference between the repetitions of individual measurements (the distance between Q1 and Q3 on the boxplot diagrams) was the smallest, regardless of the type of aqueous medium when ultrasound and Calgon were applied in combination (T4).

At Cambisol A, B horizons (S2: Keszthely A [*Cambisol*] and S3: Keszthely B [*Cambisol*]) and Luvisol A, B horizons (S4: Várvölgy A [*Luviso*l] and S5: Várvölgy B [*Luvisol*]) *(Figures 4* and *5)* DIW released most of the clay content in T1, and there was no significant difference in the dispersing effect in T2 (except for S5, where TW dispersed the most).

In T3, only DIW had the significantly highest dispersing effect, while in T4 the results were mixed (significantly or non-significantly, TW medium released the most clay or TW and DIW clay contents were almost the same).

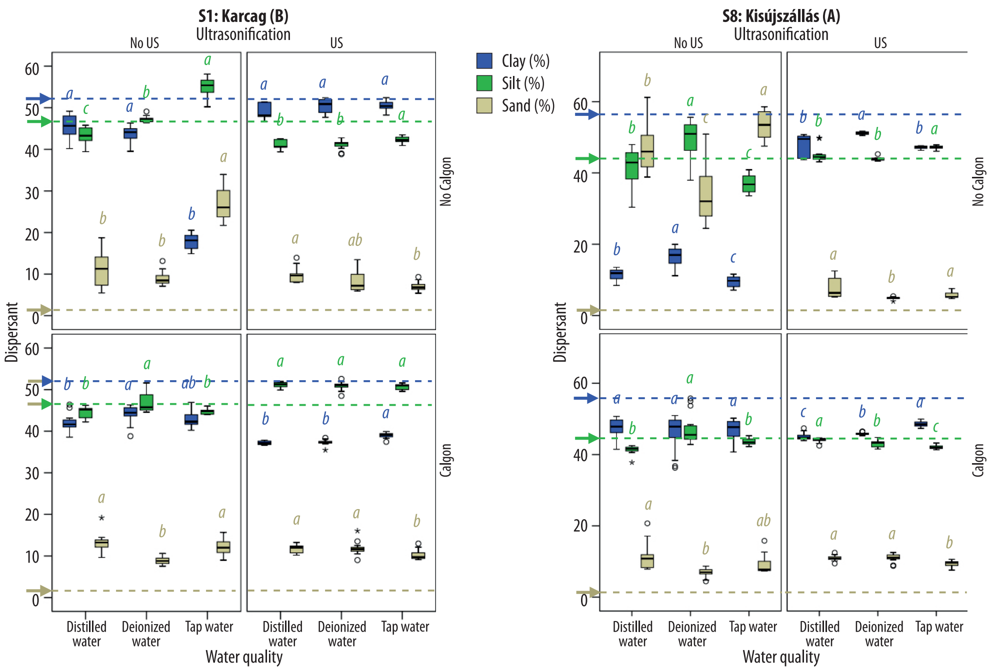

Fig. 3. Changes in clay, silt and sand content (particle size fractions – PSF) measured by laser diffraction method (LDM) in various aqueous media, grouped by soil sample tested – comparison of S1: Karcag (*Solonetz*) and S8: Kisújszállás (*Vertisol)* samples. Letters (a–c) indicate significantly different ($p < 0.05$; One-way ANOVA) mean PSF values (in ABC order the mean values decrease). The coloured arrows indicate the PSF determined by sieve-pipette method (where the colours correspond to the colours of the PSF determined with LDM). *Source*: Elaborated by the authors.

For the *Cambisol* samples (S2; S3), we can expect a small textural difference between the A and B horizons (with a higher clay content in the B horizon). In the case of the *Luvisol* samples (S4; S5), this difference was significant between the A and B horizons (as observed in the SPM measurements according to the ISO standard (see *Table 1*)). However, this texture differentiation was not always detectable in the results of the LDM PSD tests.

In the *Cambisol* A and B horizon samples (S2; S3), the highest total clay content was measured in TW with the use of US and Calgon (T4) (A horizon: 33.48% clay; B horizon: 30.07% clay) (*Table 3*, *4* and *5*). Dispersion proved to be the most effective in this case. However, the LDM determined a significantly higher clay content than the ISO SPM (~ 21–23%) (see *Table 1*).

Differences in PSF were experienced at all soil profiles only in the DW media with the T2 treatment (and to some extent with T3), in the DIW media with T2 and T3, and in the TW media with T2 (and to a lesser extent with T3 and T4) in the *Luvisol* soil (S4; S5) profile.

Figure 6 compared the particle size fractions determined from LDM PSD results of the two soil samples in various aqueous media (S6: Magyarszombatfa [*gleyic Luvisol*]; S7: Kápolnásnyék [*calcic Chernozem*]. It could be seen that for S6, in the pre-treatments without Calgon (T1 and T3), the order of clay dispersion was DIW > TW > DW, while with the addition of Calgon (T2 and T4), it was TW > DIW = DW. For S7, the deviation between Calgon and non-Calgon treatments was not as clear. In the case of T1 (neither US nor Calgon), the dispersion order was DW = DIW > TW.

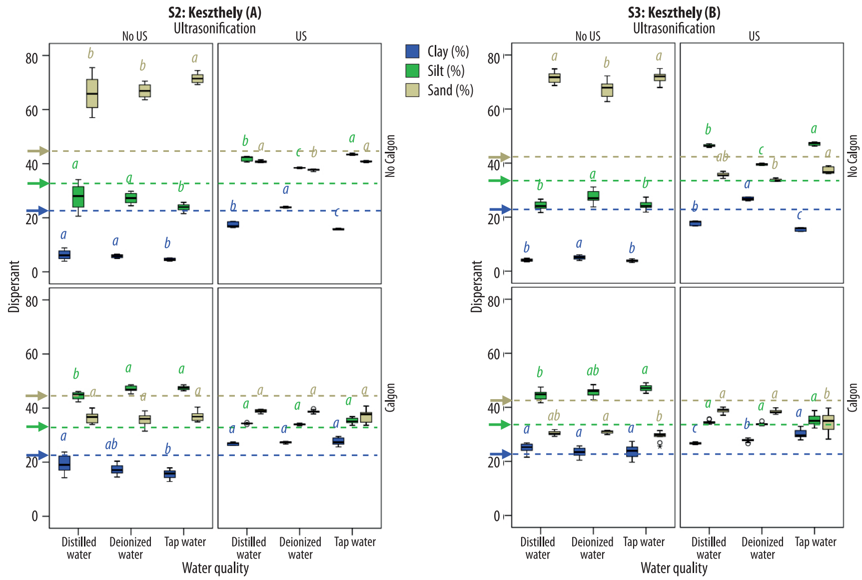

Fig. 4. Changes in clay, silt and sand content (particle size fractions – PSF) measured by laser diffraction method (LDM) in various aqueous media, grouped by soil sample tested – comparison of S2: Keszthely [*Cambisol*], and S3: Keszthely [*Cambisol*] samples. Letters (a–c) indicate significantly different ($p < 0.05$; One-way ANOVA) mean PSF values (in ABC order the mean values decrease). The coloured arrows indicate the PSF determined by sieve-pipette method (where the colours correspond to the colours of the PSF determined with LDM). *Source*: Elaborated by the authors.

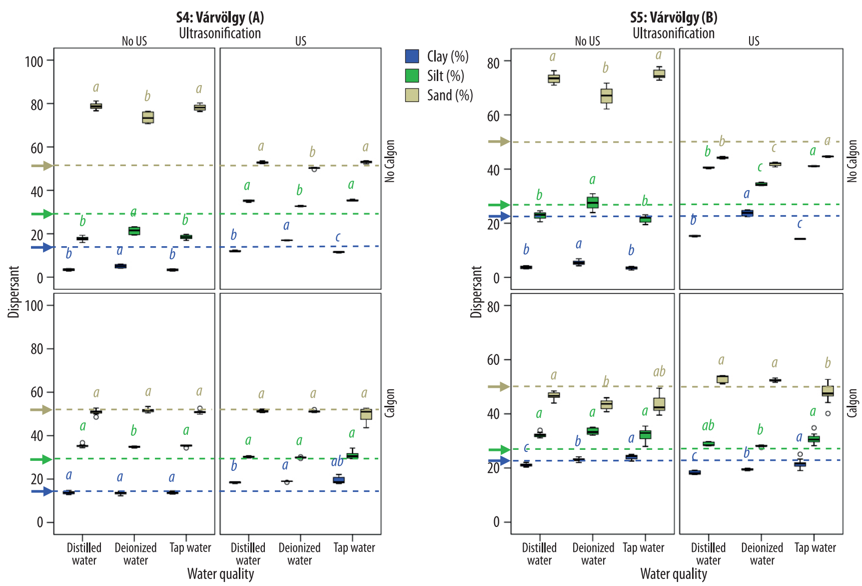

Fig. 5. Changes in clay, silt and sand content (particle size fractions – PSF) measured by laser diffraction method (LDM) in various aqueous media, grouped by soil sample tested – comparison of S4: Várvölgy [*Luvisol*], and S5: Várvölgy B [*Luvisol*] samples. Letters (a–c) indicate significantly different ($p < 0.05$; One-way ANOVA) mean PSF values (in ABC order the mean values decrease). The coloured arrows indicate the PSF determined by sieve-pipette method (where the colours correspond to the colours of the PSF determined with LDM). *Source*: Elaborated by the authors.

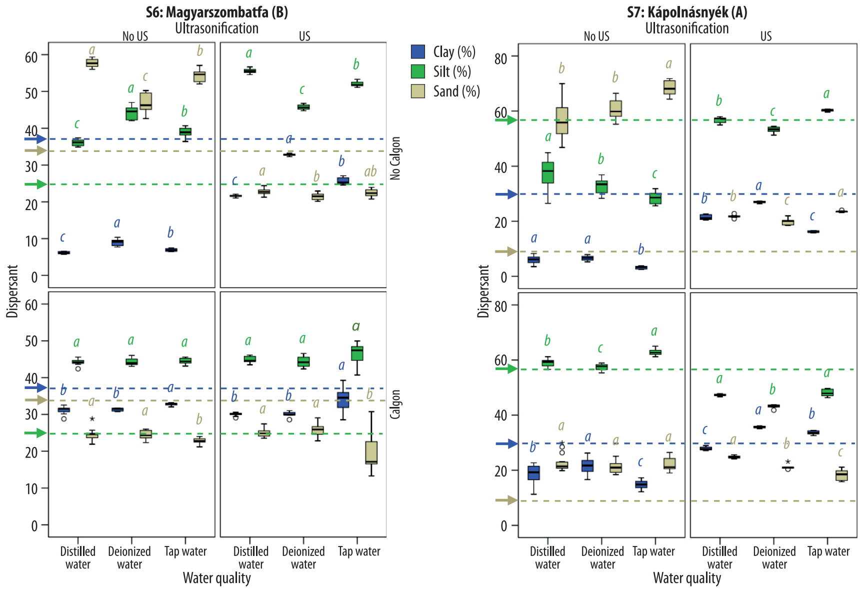

Fig. 6. Changes in clay, silt and sand content (particle size fractions – PSF) measured by laser diffraction method (LDM) in various aqueous media, grouped by soil sample tested – comparison of S6: Magyarszombatfa [*gleyic Luvisol*], and S7: Kápolnásnyék [*calcic Chernozem*] samples. Letters (a–c) indicate significantly different ($p < 0.05$; One-way ANOVA) mean PSF values (in ABC order the mean values decrease). The coloured arrows indicate the PSF determined by sieve-pipette method (where the colours correspond to the colours of the PSF determined with LDM). *Source*: Elaborated by the authors.

When only one of the pre-treatments was applied (US or Calgon), the dispersion order was as follows: DIW> DW > TW. For the combined T4 (US+Calgon), this order changed slightly to DIW > TW > DW.

In the case of TW, the variation of measured silt and clay contents in the S7 soil also increased in the combined treatment. In contrast, for S6, the silt fraction was higher for the US treatment than for the other treatments, while the clay content remained similarly higher for all three treatments than for no treatment. The slightly diverse behaviour of S5 compared to the previous three samples could be explained by a presumably higher Fe-oxide/hydroxide content (3% compared to 0–2% goethite content in the previous three) and/or by a various clay mineral composition (in this sample the amount of swelling clay mineral was 5% compared to only 2% in the previous three).

The mineral and chemical compositions of the S6 and S7 soils differed from the other samples tested. The S6 contained a significant amount of goethite mineral (10%), presumably with a higher iron content, while the S7 sample contained calcite mineral (10%) with a medium carbonate content (9.52%). The organic matter content of S7 was also high, with the calcium humates forming stable aggregates (crumbs).

When comparing the various treatments (see *Tables 3, 4* and *5*), it could be said that for both soils in all three aqueous media, the lowest clay content was measured in T1, and in general the highest was measured in T4. There were exceptions to the latter, e.g. in the case of S1 sample, where the lowest clay content was measured in the combined treatment of any of the liquid media used.

Furthermore, at S5 samples in all liquid media, the chemical dispersion with Calgon proved to be the most successful, and at S8 US treatment resulted higher clay content in DIW and DW and a similar rate of dispersion was obtained using any of the treatments (T2-T3) in TW.

*Table 3. Comparison of LDM clay, silt and sand contents measured in distilled water (DW) by treatment – within a soil sample**

Distilled water								
Soil sample	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Clay (%)								
No US - No Calgon	45.53 *a*	6.26 *c*	4.10 *c*	3.47 *d*	3.70 *d*	6.18 *c*	6.02 *c*	11.48 *c*
No US - Calgon	42.13 *b*	18.96 *b*	24.92 *a*	13.81 *b*	21.18 *a*	31.14 *a*	18.38 *b*	47.39 *ab*
US - No Calgon	45.95 *ab*	17.32 *b*	17.87 *b*	12.07 *c*	15.29 *c*	21.63 *b*	21.39 *b*	47.49 *a*
US - Calgon	36.15 *c*	26.83 *a*	24.22 *a*	18.41 *a*	18.26 *b*	30.05 *a*	27.87 *a*	45.03 *b*
Silt (%)								
No US - No Calgon	43.29 *b*	27.74 *d*	24.26 *c*	17.74 *c*	22.82 *d*	36.09 *c*	37.38 *d*	41.68 *ab*
No US - Calgon	44.51 *b*	44.54 *a*	44.58 *a*	35.31 *a*	32.19 *b*	44.20 *b*	58.95 *a*	41.28 *b*
US - No Calgon	44.15 *b*	41.90 *b*	46.47 *a*	35.13 *a*	40.52 *a*	55.61 *a*	56.84 *b*	45.15 *a*
US - Calgon	49.40 *a*	34.31 *c*	33.21 *b*	30.23 *b*	28.77 *c*	44.85 *b*	47.32 *c*	44.04 *a*
Sand (%)								
No US - No Calgon	11.18 *ab*	66.00 *a*	71.64 *a*	78.79 *a*	73.49 *a*	57.72 *a*	56.60 *a*	46.84 *a*
No US - Calgon	13.37 *a*	36.50 *c*	30.50 *d*	50.87 *c*	46.63 *c*	24.66 *b*	22.67 *bc*	11.33 *b*
US - No Calgon	9.90 *b*	40.78 *b*	35.65 *c*	52.80 *b*	44.19 *d*	22.75 *c*	21.77 *c*	7.35 *c*
US - Calgon	14.45 *ab*	38.86 *c*	42.57 *b*	51.36 *c*	52.97 *b*	25.11 *b*	24.80 *b*	10.92 *b*

*Means marked with the same letter did not significantly differ at $p < 0.05$ (One-way ANOVA). Within a fraction, soils with similar "patterns" (where the proportions of fractions measured in each treatment were similar) were marked with similar colours.

In general, the Calgon treatment resulted the highest amount of silt fraction in forest soils, almost independent of the quality of the liquid media. The higher sand content of the untreated samples (T1) was only observed for DW and DIW in S1, but not in TW.

The variation in particle size fractions determined by different combinations of chemical and dispersion effects varied from soil to soil (colours of *Tables 3, 4* and *5*). The effect of the liquid phase was less pronounced, but modified the results.

Discussion

Variation in particle size fractions by preparation and measurement methods

It is common practical experience that various preparation and pre-treatment procedures are lengthy, and therefore, in many cases, these are reduced in LDM PSD measurements (e.g. aggregate adhesives are not removed before measurements, disaggregation is considered to be taken care of by

Table 4. Comparison of LDM clay, silt and sand contents measured in deionized water (DIW) by treatment – within a soil sample*

Deionized water								
Soil sample	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Clay (%)								
No US - No Calgon	43.71 *b*	5.82 *d*	5.06 *d*	5.08 *d*	5.47 *c*	9.00 *d*	6.61 *d*	16.34 *c*
No US - Calgon	44.12 *b*	17.28 *c*	23.32 *c*	13.49 *c*	23.06 *a*	31.33 *b*	21.57 *c*	45.98 *b*
US - No Calgon	50.41 *a*	23.87 *b*	26.77 *b*	16.99 *b*	23.75 *a*	32.79 *a*	26.97 *b*	51.16 *a*
US - Calgon	37.32 *c*	27.30 *a*	27.80 *a*	18.94 *a*	19.47 *b*	30.05 *c*	34.27 *a*	45.88 *b*
Silt (%)								
No US - No Calgon	47.24 *b*	27.28 *d*	27.47 *d*	21.45 *d*	27.48 *b*	44.18 *ab*	32.80 *d*	48.98 *a*
No US - Calgon	47.05 *b*	47.04 *a*	45.80 *a*	34.81 *a*	33.47 *a*	44.33 *b*	57.43 *a*	47.18 *ab*
US - No Calgon	41.12 *c*	38.44 *b*	39.53 *b*	32.75 *b*	34.37 *a*	45.79 *a*	53.27 *b*	43.93 *b*
US - Calgon	50.90 *a*	33.99 *c*	33.81 *c*	29.89 *c*	28.14 *b*	44.34 *ab*	45.03 *c*	43.08 *c*
Sand (%)								
No US - No Calgon	9.04 *b*	66.90 *a*	67.47 *a*	73.47 *a*	67.04 *a*	46.83 *a*	60.59 *a*	34.68 *a*
No US - Calgon	8.83 *b*	35.68 *c*	30.88 *d*	51.70 *b*	43.47 *c*	24.33 *b*	21.00 *b*	6.84 *c*
US - No Calgon	8.47 *b*	37.69 *c*	33.71 *c*	50.26 *c*	41.88 *c*	21.42 *c*	19.75 *b*	4.91 *d*
US - Calgon	11.78 *a*	38.72 *b*	38.38 *b*	51.17 *b*	52.40 *b*	25.61 *b*	20.70 *b*	11.04 *b*

*For footnote see *Table 3.*

ultrasonic treatment and the addition of dispersant to the suspension is either regarded as important or not). However, our results proved that all treatments caused breakdown of aggregates, but to different degrees. It could also be seen from the interquartile range values of particle size fractions (PSF – *figures 3–6*), and the comparison of the results of SPM (with full preparation) and LDM methods that the disaggregation of unprepared and untreated samples was insufficient for accurate, reproducible quantification of elemental particle size fractions. (Assuming that the ISO standard SPM method was successful in breaking down the aggregates to a high degree and releasing the whole clay fraction.)

LDM tests usually largely "underestimated" the clay content compared to the SPM method, even for treated samples. In many cases, the difference in silt fractions between LDM and SPM was significant, which also reflected that the degree of disaggregation of samples that could be achieved by different treatments could vary considerably.

In general, the silt contents were "overestimated" for all except the T1 measurements, while the sand contents were "underesti-

*Table 5. Comparison of LDM clay, silt and sand contents measured in tap water (TW) by treatment – within a soil sample**

Tap water								
Treatment	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Clay (%)								
No US - No Calgon	17.94 *d*	4.58 *c*	3.94 *d*	3.39 *d*	3.46 *d*	6.89 *c*	3.22 *c*	9.49 *b*
No US - Calgon	42.97 *b*	15.57 *b*	23.47 *b*	13.82 *b*	24.03 *a*	32.74 *a*	14.75 *b*	46.88 *a*
US - No Calgon	50.53 *a*	15.76 *b*	15.59 *c*	11.56 *c*	14.21 *c*	25.66 *b*	16.20 *b*	46.18 *a*
US - Calgon	39.00 *c*	33.48 *a*	30.07 *a*	19.34 *a*	21.68 *b*	34.04 *a*	37.10 *a*	47.73 *a*
Silt (%)								
No US - No Calgon	55.00 *a*	23.82 *d*	24.41 *c*	18.40 *c*	21.55 *c*	38.94 *c*	28.53 *d*	37.17 *d*
No US - Calgon	44.76 *c*	47.41 *a*	47.22 *a*	35.31 *a*	32.37 *b*	44.46 *b*	62.93 *a*	43.63 *b*
US - No Calgon	42.38 *d*	43.42 *b*	47.16 *a*	35.40 *a*	41.14 *a*	52.05 *a*	60.28 *b*	47.97 *a*
US - Calgon	50.72 *b*	36.87 *c*	35.37 *b*	31.00 *b*	30.75 *b*	46.47 *b*	50.67 *c*	41.38 *c*
Sand (%)								
No US - No Calgon	27.06 *a*	71.59 *a*	71.73 *a*	78.21 *a*	74.99 *a*	54.18 *a*	68.24 *a*	53.33 *a*
No US - Calgon	12.26 *b*	37.02 *c*	29.31 *c*	50.86 *c*	43.61 *b*	22.80 *b*	22.30 *bc*	9.50 *b*
US - No Calgon	7.09 *c*	40.81 *b*	37.25 *b*	53.04 *b*	44.65 *b*	22.29 *b*	23.52 *b*	5.85 *c*
US - Calgon	10.29 *b*	29.65 *bc*	34.55 *b*	49.66 *bc*	47.57 *b*	19.50 *b*	12.23 *c*	10.89 *b*

*For footnote see *Table 3.*

mated" for all except the T1 LDM measurements. It can be seen from *Figure 2* that the LDM measurements were least successful in achieving total disaggregation at T1, and were the most effective at T4 for DW and T2 and T3 for DIW. From *Figure 2* it was likely that the micro- and macro-aggregates in the sand fraction were disintegrated into elementary particles (clay, silt and sand) and micro-aggregates (mainly to sizes corresponding to the silt fraction) by the T2-T4 treatments but that complete disintegration of aggregates did not generally occur.

It was also puzzling why the median values of LDM sand contents in the boxplots were systematically smaller than the medians of the measured SPM values (see *Figure 2*). Where did part of the sand fraction go? It is possible that with maximum ultrasonic action and mixing, the entire sand fraction could disintegrate due to "too strong" dispersion effects. However, it was not consistently followed by a more significant disintegration of the silt fraction. Further research in this direction should be needed, as some literature has reported that sand fractions measured by conventional methods are often "under- or "overestimated" by LDM methods depending on the type of apparatus and even the design of the preparation units (Sochan, A. *et al.* 2012; Polakowski, C. *et al.* 2015; Mattheus, C.R. 2020; Stevenson, A. *et al.* 2023).

Effect of the physical and chemical dispersion

Dispersion rates were lowest for all aqueous media in T1, because elementary particles could not be separated during the measurement without pre-treatment even if a slight spontaneous disaggregation effect of the aqueous medium may be prevailed (e.g. in dispersive soils). Generally, higher clay content and the smaller standard deviation between the individual measurement repeats suggested that the disaggregation was the most complete in the T4 among each LMD measurement.

If some pre-treatment was applied, the greatest variation was in the silt fraction. The measurable amount of this fraction was significantly affected by the quality of the liquid media. The high interquartile range also showed that the amount of partial disaggregation varied with soil properties and the type of liquid media. The outliers under treatments were also more significant in the silt fraction, indicating that the effect of pre-treatment was most critical in determining this fraction (which obviously affected the measurement results of other fractions). The uncertainty of the measurement results was also reflected in the large variation in the clay content that could be determined by different treatments.

It is questionable, however, how to explain the small, although not significant, increase in the median of sand content at T4 treatment compared to T3 and T2 treatments, despite the lack of parallel statistically verifiable changes in the other fractions in this comparison. It is also interesting to note that the resulting clay content followed a similar "disaggregation pattern", being much higher in the T2-T4 treatment than in the T1 treatment (untreated samples).

It was also the case that disaggregation and dispersion of well-structured soils with high aggregate stability (such as the S6 [*gleyic Luvisol*], and S7 [*calcic Chernozem*]) occurred in several stages, and it is a question of which stage we "caught" and measured the particle size distribution during our measurements. Thus, the "particles" measured by the LDM method can in many cases, be a mixture of aggregates and elementary particles of different sizes (e.g. Buurman, P. *et al*. 1997). It is very difficult to separate elementary particles from small micro-aggregates and even from "composite building units" of elementary particles in lower size ranges (Totsche, K.U. *et al.* 2018).

In the sequence of pre-treatments, the macro-aggregates in the sand fraction were increasingly transformed into micro-aggregates in the silt fraction, and then, towards T4, a larger part of these micro-aggregates were also broken up and some of the particles were measured in the clay fraction. This trend was broadly supported by the boxplot diagrams of sand contents in the three aqueous media (see *Figure 2*). Similar, "intermediate" dispersion states in various aqueous media had been reported by the authors in other research investigating PSD or ASD of soils and sediments (e.g. Goosens, D. *et al.* 2014; Abdulkarim, M. *et al*. 2021). The variable number of outliers for treatments may indicate that different dispersion states could be achieved with various degrees of disaggregation depending on soil properties.

Sometimes, not only the partial disaggregation but flocculation, precipitation and the formation of artefacts were occurred (e.g. in high colloid and/or sodium content soils), as noted by also Shein, E.V. *et al.* (2006), Tan, X. *et al.* (2017), and Abdulkarim, M. *et al.* (2021). These were due to soil/aqueous media, soil/dispersant or aqueous media/dispersant interactions and varied depending on the treatment applied and soil properties. Calgon is used as a dispersing agent to saturate the negatively charged surfaces of soil with Na^+.

The required Calgon concentration might depend on the soil's CEC value and the quality of the adsorbed cations. When comparing the effect of each treatment on the S1, it was seen that T1 and T3 released the most clay particles from the aggregates in DW, and T3 in DIW and TW. With the addition of Calgon solution (T2 and T4), the salinity of the fluid increased significantly, thus, enhancing flocculation effects in the system. Therefore, the rate of clay dispersion was lower with Calgon only (T2) than with sonification only (T3).

Presumably, therefore, this was not primarily a function of the properties of the liquid but rather the result of the interaction between the solid and liquid phases and the dispersant, which could be enhanced or weakened by the effect of the US (re-aggregation or flocculation of the components). A similar result was obtained, e.g. by Abdulkarim, M. *et al.* (2021), who explained this by complex simultaneous or specific processes. In addition, the dispersing effect of Calgon (repulsive effect of increasing Na^+ content; complexing ability of NaHMP; increasing the pH of the suspension and reducing positively charged surfaces) depended on the proportion of Na^+ present and able to act in the suspension. The CEC value (which, for example, is twice as high in *Chernozem* soil compared to *Luvisol* soil) related to the amount and quality of the adsorption sites, colloid surfaces, e.g. the clay content, the mineral composition (including Fe-(oxi)hydroxides content), and the presence and quality of organic matter. Calgon should form calcium-phosphate and calcium-carbonate precipitates in soil when the measurement occurs in tap water or hard water (Buurman, P. *et al*. 1997).

Insufficient or excessive addition of Calgon (both dependent on soil properties) could also lead to erroneous measurements (Murray, M.R. 2002; Kaur, A. and Fanourakis, G. 2018). It is likely that the amount of Calgon solution to be added could be optimized even by soil type (Kaiser, M. *et al.* 2012). However, since this complicates the standardization of measurements, the most widely used concentrations are those specified in the ISO 11277:2009(E) standard.

Effect of soil properties

To summarise, *figures 3–6*, and *tables 3–5* showed that all soils gave different "responses" to various levels and types of disaggregation and dispersion (chemical and/or physical). The extent of these responses, therefore varied with the type of treatments applied, and potentially different size ranges of aggregates/non-elementary particles were affected, according to a "pattern of disaggregation" (disaggregation and/or dispersion processes).

For example, while in the case of DW measurements, the clay content of the S1: Karcag (*Solonetz)* untreated sample (T1) showed both positive and negative variation between treatments, the clay content of the S7: Kápolnásnyék [*calcic Chernozem*] sample increased monotonically in T1-T4.

The sample with high sodium content (S1) exhibited a significantly distinct disaggregation pattern from the other samples due to major dispersion, even with low disaggregation effects/forces. This may indicate that, in addition to spontaneous disintegration on contact with the liquid phase (Amézketa, E. *et al.* 2003), there was rapid disintegration of weakly bound particles/aggregates. All three treatments showed similar effectiveness to the applied full preparation at the SPM. In general, the "dispersion pattern" of the tested S1 sample pre-treatment showed huge deviations compared to the other tested soil samples for all measurements in various aqueous media (see *Table 3*, *4* and *5* – purple colouring).

The particle size fractions of the tested S2: Keszthely (A) [*Cambisol*]; S3: Keszthely (B) [*Cambisol*] and S4: Várvölgy (A) [*Luvisol*]; S5 Várvölgy (B) [*Luvisol*] (see *Figure 4* and *5*) showed that the dispersing, disaggregating effect of the aqueous media varied depending on the pre-treatment.

Comparing the dispersing effect of each pre-treatment on different soils, we measured the significantly highest clay content with the T4 (combined treatment) in all aqueous media for the S2 and S4 samples. For the S3 sample, we observed similar results. However, for S5, the T2 resulted the best dispersing effect in DW and TW media, while for DIW, T3 released the highest amount of clay (see *Table 3*, *4* and *5*). These soil samples are more similar to each other than to the soils of the first group (upper genetic horizons of forest soils with various organic matter contents), which may explain their similar disaggregation and dispersion behaviour.

When TW was used in the LDM measurement, at S7: Kápolnásnyék (*Chernozem)* soils silt and clay contents also increased in the combined treatment (the distance between Q1 and Q3 increased in the boxplot plots), suggesting the formation of possible Ca phosphate precipitates from Calgon and calcium carbonate in TW (possibly soil) (see Buurman, P. *et al*. 1997) (see *Figure 6*). In some cases, for example at S6: Magyarszombatfa [*Luvisol*], the more effective treatment (at least the more silt content) was experienced by the use of only US. The chemical and physical dispersion (and sometimes the degree of flocculation) can also vary depending on the mineral composition of the soil (e.g. Goossens, D. *et al*. 2014; Tan, X. *et al*. 2017; Polakowski, C. *et al*. 2023). In this sample, the role of iron hydroxides/oxihydroxides, which hold aggregates together, may be the most crucial in dispersion. Fe-oxides/hydroxides can play an important role in the formation of not only micro- but also macro-aggregates due to their high specific surface (Totsche, K.U. *et al.* 2018; Kirsten, M. *et al.* 2021). If some of these transform into goethite, a crystalline form with a smaller specific surface area and lower reactivity, the active (mainly non-crystalline) iron content may decrease, altering the stability of aggregates (e.g. Kögel-Knabner, I. *et al.* 2008; Kaiser, M.K. *et al.* 2011; Regelink, I. *et al.* 2013). This may also determine the applicability of LDM PSD analysis for samples with higher iron content.

With increasing soil organic matter content, aggregate stability increases only within certain limits. The stability of aggregates depends on the quality of organic matter (Amézketa, E. 1999; Tyugay, Z. *et al.* 2010; Schulte, P. *et al.* 2016; Li, S. *et al.* 2023). This is also reflected in the characteristic disaggregation patterns of the S1: Karcag (*Solonetz)* sample with higher sodium humate content and the S7: Kápolnásnyék (*Chernozem)* sample containing mainly calcium-humates. We had less opportunity to investigate the effect of carbonates as components responsible for the stability of the aggregates, as the soils studied are mostly carbonate-free. Moreover, the colloidal effects responsible for aggregation may not only be cumulative but may also be mutually reinforcing (Amézketa, E. 1999; Shein, E.V. *et al.* 2006; Schulte, P. *et al.* 2016; Totsche, K.U. *et al.* 2018). This may be the reason why some, either chemical or mechanical, or various intensities treatments may cause different degrees of disaggregation or even re-aggregation.

The dispersion pattern and behaviour of soils against disaggregation and dispersion forces also depend on their aggregate stability. More dispersible soils and even soil with higher aggregate stability might show similar PSF results at a given soil for any of the treatments (T2-T4), without preparation. But the reasons for this may be different. In the former case, a rapid high amount of dispersion and in the latter case, the fact that treatments are insufficient may lead to this (see *Table 3*, *4* and *5*). Soils differ in their aggregate stability (Bronick, C.J. and Lal, R. 2005), and different soil constituents and binding forces form aggregates in various aggregate size ranges (Amézketa, E. 1999). Thus, different preparation and pre-treatment methods may be recommended prior to PSD measurements depending on the physical, chemical and mineral properties of the soils (Schulte, P. *et al.* 2016; Fisher, P. *et al.* 2017). These relationships might reveal high complexity, a dynamic "equilibrium aggregation" (Totsche, K.U. *et al.* 2018) is formed in the soil for each combination of soil properties, which might be affected by the changes of "external" conditions (e.g. dispersing forces or quality, hardness or pH of the liquid media) or "internal" conditions (e.g. rate of adsorbed cations, flocculation/dispersion of colloids). This may be the reason why, according to the experiences, the role of soil properties (e.g. organic matter content and quality, clay content and quality, carbonate content, etc.) varies enormously and may even have opposite effects on stability (e.g. Amézketa, E., 1999; Mamedov, A.I. *et al.* 2016; Virto, I. *et al.* 2011; Balázs, R. *et al.* 2011; Kaiser, M. *et al.* 2012; Kögel-Knabner, I. *et al.* 2008; Almajmaie, A. *et al.* 2017; Totsche, K.U. *et al.* 2018). In the case of well-structured aggregated soils, a combination of physical and chemical disaggregation and dispersion techniques is therefore recommended (Shein, E.V. *et al.* 2006; Tyugay Z. *et al.* 2010; Abdulkarim, M. *et al.* 2021).

Effect of the aqueous media quality

Neither manuals for LDM measurement instruments nor practice gave precise instructions on the quality of the liquid phase to be used in the measurement. If all soils were considered together, the effect of liquid quality on the effectiveness of disaggregation processes was really less noticeable (it was not always significant).

However, when the differences in PSF values for soils with different soil properties were examined separately *(figures 3–6, tables 3–5)*, it was found that the quality of the liquid phase (e.g. ionic composition, hardness, interaction with soil, dispersant, etc.) might have influenced the results. In the case of the sample with high Na^+ content, a significantly higher clay content was measured with tap water (TW) in the combined treatment (T4) than in other aqueous media. Parallel to this, particularly the sand content was lower. This might have been due to the addition of Calgon solution with high salt content to the tap water with also high salt content. This system was subjected to prolonged (240 seconds), high-energy (40 kHz) ultrasonic treatment, which facilitated ion dissociation and an increase in pH, thereby making dispersion more effective (Matouq, M. 2008). TW is a medium-hard water in the sense that its pH is moderately alkaline and contains higher amounts of salts (mainly Ca/Mg carbonates and bicarbonates, etc. – *Table 2*). This means that depending on the ionic composition of the solution, there are different possibilities for structural changes resulting from solid-liquid phase interactions (e.g. ion exchange, dissolution of salts).

Regarding the effect of aqueous media DW was applied, the clay content pattern of the more clayey B horizons of forest soils (S3, S5, S6) was similar, but the higher organic matter content A horizons of forest soils (S2 and S4) were in a different group. Similar experiences were described for the behaviour of the soils in DIW treatments, but similar pattern for clay content was observed for S2-S4 soils and other pattern for soils with higher clay content S5, S6 and S8. Soils with characteristic soil properties could have been better distinguished in distilled water, which might have referred to lower interaction between solid-liquid phases than in measurement with tap water (see *Table 3*, *4* and *5*).

Among the aqueous media, the most distinct dispersion of the soils in sand and clay content was observed in the TW measurement, which might have been due to the varying degrees of dispersion, probably incomplete, in this medium. The "patterns" of disaggregation in the TW measurements were significantly different from the previous two aqueous media. It could be assumed that these results reflected, for example, the differences in CEC between soils, as higher CEC allowed for a higher degree of ion exchange during PSD measurement (Mason, A. *et al.* 2011; Tan, X. *et al.* 2017), which affected the aggregate stability variously up to other soil properties. Depending on the liquid phase and the quality of the original soil solution, even precipitates might have formed (Shein, A.V. *et al.* 2006). However, fluids affected the measurement results differently, relying on the dispersing effect and the dispersant used in the LDM measurement and the amount of dispersant used.

Conclusions

The aim of our research was to elucidate the effect of the quality of the aqueous media on the amount of particle size fractions (PSF) determined from LDM PSD measurements in the case of soils with certain extreme properties (e.g. high clay or exchangeable Na^+ content, variable organic matter content).

We also investigated how the two most commonly used treatments (Calgon dispersant/ultrasonic dispersing) and their combinations affected the PSFs when various aqueous media were applied. Also, how did these PSF results change depending on the above compared to the SPM ISO standard PSD results?

To summarise, all soils gave different "responses" to various levels and types of disaggregation and dispersion with no pretreatment or applying Calgon and/or ultrasound. The extent of these responses will therefore vary with the type of treatments applied, and potentially different size ranges of aggregates/non-elementary particles may be affected, according to a "pattern of disaggregation/dispersion".

– The primary reason is that, according to the methodology used for LDM PSD measurements, soil aggregates were generally *only partially disaggregated* by ultrasonic and chemical dispersion or a combination of both. The degree of disaggregation can vary depending on the micro- and macro-aggregate stability determined by the physical, chemical and mineralogical properties of the soils (e.g. soils with high Na^+ content and low aggregate stability were well disaggregated by the dispersion methods used, whereas samples with high organic matter content or iron oxide content and high aggregate stability were poorly disaggregated). Thus, although of varying importance depending on the aggregate stability, it is considered necessary to assist the disaggregation of samples by removing aggregate-stabilising adhesives prior to LDM PSD measurements.
– The degree of disaggregation depends not only on soil properties but also on the *choice of dispersion methods*. In some of the soils studied, the combination of ultrasonic and chemical dispersion resulted in the highest degree of disaggregation, with clay content being released from macro- and micro-aggregates. For other soils, better results were obtained when only one type of dispersion method was used. The use of a chemical dispersant (Calgon) may, for example, result in the formation of artificial products (Ca-phosphates) in the presence of Ca^{2+} ions, or the combination of chemical dispersion and ultrasound may have a flocculating effect in the suspension.
– Another important finding was that the *choice of the aqueous media* used also affected the reliability and accuracy of LDM PSD results. The chemistry, ion content and soluble salt content of the aqueous media can influence the degree of disaggregation, the degree of dispersion and flocculation, the ion exchange processes and the formation of artificial products. The optimum aqueous media for more complete disaggregation varied depending on the soil properties and the dispersion methods used.

Our results point to the need for standardisation of the LDM PSD measurement methodology since only in this way can the results of the different laboratories be compared. They also call attention to the need to find a solution to ensure a more accurate determination of the particle size distribution of soil samples with extreme properties (by complete disaggregation where possible, complete dispersion of elementary particles, and elimination of artificial product formation) while maintaining the speed advantages of the LDM PSD methodology.

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GIS and soil property-based development of runoff modelling to assess the capacity of urban drainage systems for flash floods

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Abstract

The extreme precipitation resulting from climate change has been causing increasingly serious damage in populated areas over the past 10–15 years. The torrents of flash floods cause significant financial damage to both the natural environment and man-made structures (such as roads and bridges). The determination of the physical geographic parameters of this phenomenon (e.g. the amount of runoff water) is significantly affected by technical uncertainties, usually due to the lack of monitoring systems. However, the application of modern geospatial tools can improve the quality of input data needed for runoff modelling. In the present study, an existing runoff model (the Stowe model) developed by ESRI was further enhanced with field measurements, soil parameters, GIS, and remote sensing data, resulting in the creation of the model named ME-Hydrograph. Finally, the two models were compared, and we examined the capacity of an urban stormwater drainage system through surface runoff modelling. The aim of the research was to create a runoff model that can be easily and quickly used. The application of this geospatial model presented in the study can be useful not only in the examination of urban stormwater drainage but also in contributing to the understanding and management of flash floods that occur in Hungary. Additionally, it can aid in the development of risk mapping related to flash floods in the country.

Keywords: soil properties, GIS, flash flood, runoff modelling

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Introduction

The increasing number of extreme precipitation events causing flash floods has posed a significant impact on various technical and scientific fields (flood management, hydrology, soil science etc.). Research related to this phenomenon has played a prominent role in recent years, particularly in the regarding of monitoring systems, valley characteristics, soil surface coverage and modelling the recession of flood waves and climate trends (Guo, L. *et al.* 2018, Jakab, G. *et al.* 2019; Du, J. *et al.* 2020; Ramos Filho, G.M. *et al.* 2021; Víg, B. *et al.* 2022; Mikes, M.Z. *et al.* 2024). The stormwater flow velocity depends on factors such as land cover and surface roughness, as different terrain features influence velocity to varying degrees (Agroszkin, I.I. *et al.* 1952; Chow, V.T. 1959). The analysis and incorporation of these additional factors into runoff modelling were first achieved with the 1995 release of HEC-RAS and HEC-HMS (Hydrologic Engineering Center's River Analysis System and Hydrologic Modelling System); however, these programs require significant input data.

In the examination of flood waves occurring in Hungary, flood wave characterization was first achieved through a detailed analysis of the accumulation-runoff process in areas where no representative water gauge station or cross-section of a watercourse was present. The resulting methods have continuously been expanded and evolved with

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other surface data (catchment characteristics and soil properties) provided by geography (Pirkhoffer, E. *et al.* 2013; Koris, K. 2021). With the development of GIS and remote sensing methods, modelling opportunities have expanded through the numerical processing of these data. However, when such extreme precipitation events (precipitation intensity above 35 mm/h (Goda, Z. 2019) are reconstructed, limitations may arise (Czigány, Sz. *et al.* 2009). Furthermore, mapping methodologies for flash flood risks are still under development due to deficiencies in the spatial resolution of hydrological and soil databases. Researchers lack data on small catchment areas surrounding settlements, as well as their runoff characteristics, and the intensity of precipitation events can vary.

The basis for designing urban stormwater drainage structures relies on methods applied in technical hydrology. However, these methods often involve approximate estimates due to the lack of incoming data (Kontur, I. *et al.* 2003). Quantitative data that provide greater technical safety, such as mapping and field assumptions (e.g. Lidar DEM, soil sampling, and laboratory analysis), are associated with significant costs. With the advancement of geospatial tools, these estimates can be optimized and improved using interdisciplinary methods. Beyond describing surface properties (slope steepness, topological wetness index, valley density, etc.), it is crucial to provide the most reliable data on the expected flood wave characteristics with minimal input data and uncertainty.

In this study, we present an assessment of the capacity of a stormwater drainage network in a settlement vulnerable to flash floods. The study goal was to develop a GIS tool for modelling surface runoff and infiltration processes for water falling on the urban surface and flowing in from the external parts of the catchment. The modelling utilized data on topography, land use, built environment, and soil conditions, supplemented with parameters from the technical description of the drainage system provided by civil engineers. The GIS-based simulation was implemented in the ESRI ArcGIS 10.1 environment. The input layers used for running the model were organized into a GIS database. Since the surface runoff-infiltration characteristics are fundamentally determined by the soils in the sample area, their physical properties and further parameters were investigated through field measurements at representative locations. To facilitate and expedite the iterative runs of the modelling, we developed a Python-based tool capable of calculating and analyzing water yields. The results of the model runs were ultimately compared with the capacity data from the technical plan documentation of the drainage system. The advantage of the model is that data are provided with high reliability despite relatively small field data sampling.

Study area

The study area is located in the eastern part of the Nyögő-Harica catchment, near the border of Sajószentpéter, in Northern Hungary *(Figure 1).* A significant portion of the catchment is situated in the northern foothills of the Bükk Mountains, in the Tardona Hills, extending into the Northern Bükk in the west, while its north-eastern part is bordered by the Sajó Valley.

Geologically, the area is located in the East-Borsod Coal Basin. The basin is composed of alternating layers of Neogene marine and lacustrine sediments of various ages, along with Miocene pyroclastics, often deposited with erosional discordance (Kozák, M. and Püspöki, Z. 1995; Kozák, M. *et al.* 1998; Harangi, Sz. 2001). Most Quaternary sediments are products of weathering from the aforementioned rocks. Due to sequential tectonic processes during the Miocene to Quaternary, the area has been fragmented in a mosaic pattern (Kozák, M. and Püspöki, Z. 1995; Pelikán, P. 2002). The area's topography is fundamentally shaped by these geological and structural characteristics (Sütő, L. 2001). The erosion rate is significant in the area, with a valley density of ~ 3.0 km/km^2 (Baros, Z. *et al.* 2001), and an average stream density in the hilly region of 2.7 km/km^2. The average relative

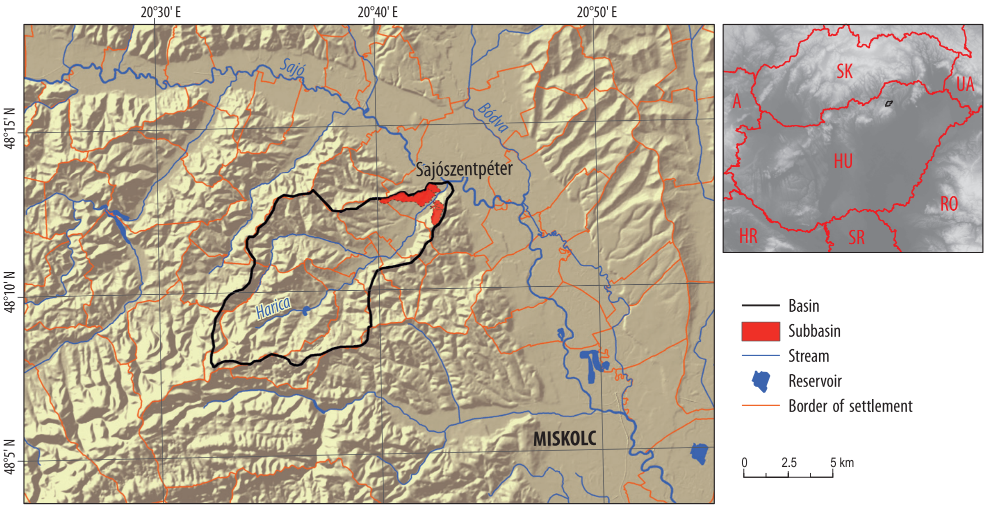

Fig. 1. Location of the study area. *Source:* Elaborated by the authors.

relief is 105 m/km², while in areas bordering the Sajó Valley, it is 80 m/km² (Dövényi, Z. 2010). The examined area has a moderately warm to moderately dry climate (Bihari, Z. *et al.* 2018), becoming moderately warm and dry around 2050 (Bihari, Z. *et al.* 2018). The annual mean temperature varies from 8.8–9.3 °C. The average maximum temperature on the warmest summer days is 31–33 °C, while the average minimum temperature on the coldest winter days is -17 °C. The annual precipitation ranges from 550 to 600 mm. The prevailing wind directions are northwest and northeast, aligning with the topography, and the average wind speed is 2.5 m/s (Péczely, Gy. 2006; Dövényi, Z. 2010). Within the study area, the main determinants of soil diversity are the parent rock and topography. In the Harica Valley Gleysols (Aqualfs) with heavy clays have developed. The northern watershed areas are covered by Stagnic Luvisols (Epiaqualfs). Areas of higher elevation are covered by loess-like, physically heterogeneous sediments, on which area Luvisols (Alfisol) have developed. The southern watershed areas are covered by eroded Arenosols (Psamments), Arenic Phaeozems (Haplustolls), and Leptosols (Lithic Alfisols) *(Figure 2).*

More than half of the Tardona Hills is covered by grass vegetation, while nearly a quarter is covered by forests. Human activity extensively transformed vegetation during the medieval period, leading to the fragmentation of forest communities. The grasslands are mainly composed of patches of fescue (*Festuca*), reed bentgrass (*Calamagrostis epigeios*), and false brome (*Brachypodium sp*). The predominant forest communities include Turkey oak forest (*Quercetum petraeae-cerris*, covering 43% of the forests) and the hornbeam-oak forest (*Caricipilosae-Carpinetum*, covering 33% of the forests) in higher regions. The proportion of forest patches composed of invasive species is considered low, with notable ones being the black locust stands (8.6% of forests) and the Norway spruce forests (*Picea abies*, 1.7% of forests) (Szirmai, O. and Czóbel, Sz. 2008).

Based on the Flood Calculation Guide issued by the General Directorate of Water Management of Hungary, the flood discharges calculated for the study area at the firth of Nyögő Stream, with a specific discharge of Q_5% m³/s km², are as follows: Q_1% = 71.0 m³/s, Q_3% = 54.6 m³/s, Q_{10}% = 38.2 m³/s (Koris, K. 2021). However, these values refer to the entire catchment area, not to the small

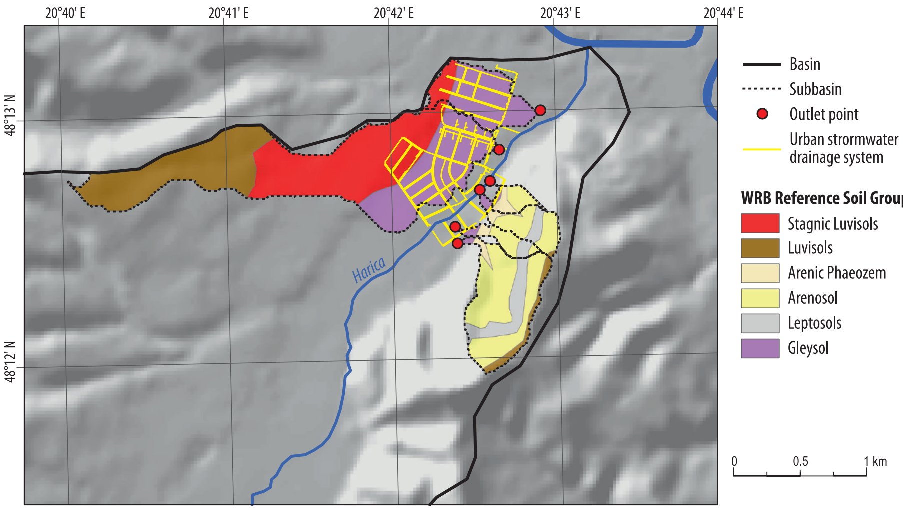

Fig. 2. Digital soil map of the study area. *Source:* Elaborated by the authors.

catchments surrounding the settlement. The Flood Calculation Guide cannot be applied to catchments smaller than 2 km² or can only be applied if there is thorough knowledge of the catchment area and the use of the so-called hydrological analogy. Therefore, new methods should be sought using GIS and remote sensing data to study catchments that are still hydrologically unexplored.

Materials and methods

Introduction of Stowe-Hydrology tool

As the first step in the research, the selection of a runoff model was necessary, with criteria requiring it to be freely accessible and user-friendly. This led to the selection of the Stowe-Hydrology model developed by ESRI (arcgis.com). The Stowe model utilizes slope steepness, flow direction, and accumulation grids derived from a digital elevation model (DEM), along with watershed boundaries and outlet points, as input data to determine runoff velocity. In this way, a general overview of surface runoff can be obtained.

Determining the runoff requires knowledge of the quantity of flowing water, as well as the size of watershed area and runoff time also. For this purpose, the runoff velocity needs to be determined using the method proposed by Maidment, D.R. *et al.* (1996). While this method accounts for spatial variability in runoff velocity, it ignores temporal changes and recession of precipitation and the amount of runoff water. In real scenarios, runoff velocity changes over time, influenced by the rate of recession. According to our current level of technical knowledge, this dynamic change is difficult to model, allowing us to obtain only a general picture of the problem. Nevertheless, it can be considered suitable for modelling larger floods (e.g. precipitation intensity above 35 mm/h), as studies conducted in Australia found that runoff velocity remains relatively constant during major floods (Pilgrim, D.H. 1976). During calculation, each pixel in the elevation model receives a velocity value based on the slope of the terrain it covers and the size of the watershed area above it. This is determined by the following equation (Eq 1, Flow Accumulation).

$$V = V_m \cdot \frac{S_b \cdot A_c}{s^b A_m^c}, \qquad (1)$$

where: V is the runoff velocity associated with the pixel of interest; V_m is the average runoff velocity characteristic to the watershed area. We assume a runoff velocity of 0.1 m/s based on Maidment, D.R. *et al.* (1996); s is the slope of the area covered by the pixel; A is the size of the contributing area to the pixel, where water is directed (Flow Accumulation); b and c are empirical exponents, which Maidment, D.R. *et al.* (1996) defined as 0.5 for similar types of areas; $s^bA^c{}_m$ is the average slope-to-watershed ratio.

The model cuts unrealistically high or low velocity values (above 2 m/s or below 0.02 m/s) and equates them to threshold values. The runoff time represents the time it takes for water to reach a specific point from the furthest point in the watershed. For the study, we used the weighted option of the ArcMap Flow Length tool. The weighting factor indicates how much time the water needs to pass through a cell. In this case, this time, in line with the above, can be calculated as the reciprocal of the velocity, 1/v, since the greater the velocity, the less time the runoff water spends on a cell. After classifying the runoff velocity, an isochrone map is generated, which provides the Unit Hydrograph (UH) to depict the surface runoff wave produced by a unit of precipitation. The hydrograph enables analysis of the intensity and temporal distribution of runoff caused by precipitation events (Maidment, D.R. *et al.* 1996).

The Stowe model does not consider precipitation intensity, land cover, surface infiltration, and storage conditions, also it can handle only one watershed at a time. Our model was developed using these input data, and a comparison was made between the two models.

Introduction of ME-Hydrograph model

We enhanced the model by developing a separate tool in Python called ME-Hydrograph, making it suitable for integration into the ArcGIS Toolbox. The new simulation model for stormwater runoff relies on numerous additional input data for calculating hydrological processes. These include precipitation data from recent years, topographical characteristics determining accumulation, spatial extent and ratio of impervious and pervious surfaces, as well as the physical properties of various soil types, especially soil saturation conditions and infiltration factors.

The new model was applied in the study of the stormwater drainage system load in the town of Sajószentpéter. The input data used were as follows: a DEM with a spatial resolution of 5 metres, precipitation data from the nearest meteorological station, Sentinel multispectral satellite images for land use mapping, as well as literature-based soil type data, surface coverage, and in-situ measured soil infiltration and saturation values extended based on field knowledge and surveys. The drainage network was designed by selecting valleys of Harica Stream that terminate in the sewage system of Sajószentpéter. Subsequently, points were chosen where these valleys join the stream. For precise alignment, we “snapped” these points to the theoretical water flow network (Snap Pour Point), and then used the Watershed command to calculate the sub-watersheds corresponding to the respective outlets. In the area, six sub-watersheds were identified from which water drains into the city’s drainage network. We analysed in details the small watershed labeled as number 5. Additional parameters will be discussed in the following sections.

Mapping of topography and surface properties of the sample area

Based on the 5 m resolution digital elevation model, the delineation of the entire catchment area, as well as the Harica and Nyögő streams, was completed. For the land-use layer, Sentinel-2b multispectral satellite imagery with a resolution of 10 metres was used, captured on 27 September 2016. The utilized channels were B2 (blue), B3 (green), B4 (red), B8 (NIR), and the 10-metre resampled B5 (VNIR). Training areas were established for the classification of individual pixels in satellite images, which were identified through a combination of field surveys and aerial photographs captured simultaneously with higher spatial resolution. The classification was performed using MultiSpec software (https://engineering.purdue.edu/~biehl/MultiSpec/), creating eight land-use categories with supervised classification.

Integration of precipitation conditions into the model

Since there is no regular precipitation measurement in Sajószentpéter, the precipitation data used for running the simulation model are derived from measurements at the nearest (Putnok) meteorological station based on Hungarian Meteorological Service database also the annual hydrometeorological reports from the General Directorate of Water Management of Hungary were further utilized *(Table 1)*. Since 2010, extreme precipitation events have been recorded almost annually in the region, leading to the development of mesoscale convective system (MCS) storms that generate flash floods. These storms are predominantly observed between April-May until October, but typically develop most frequently during the summer months.

Mapping of soil properties of the sample area

The purpose of the soil survey was to provide input data based on real measurements and field experiences. The soil diversity within the watershed significantly influences the surface runoff of precipitation. A portion of the precipitation infiltrates into the soil and then, after the soil is saturated, begins to flow on the surface. To quantify this phenomenon, we measured the soil infiltration rate at five locations using a ring infiltrometer, and soil profiles were also excavated, and soil samples were sent to laboratory for analyses. The main purpose of the "constant head" method used to measure the amount of water infiltrating into the soil per unit of time is to place two metal frames into the top 30 cm of soil. The outer frame provides constant hydrostatic pressure to ensure that the water in the inner frame infiltrates deeper into the soil and does not escape laterally (Várallyay, Gy. and Fórizs, J. 1966).

During the infiltration test we examined how land cover, especially traditional agricultural cultivation, affects the structure of soils, influencing their water-conducting and water-retaining capacities. At sampling sites 1 and 2, where the frames were placed 40 metres apart on the same soil type but under different cultivation intensities, the infiltra-

Table 1. Daily precipitation totals during MCS stroms

Date	Precipitation amount, mm/24 h	Date	Precipitation amount, mm/24 h
06.05.2010	34.2	22.10.2014	34
15.05.2010	60.4	17.08.2015	33
16.05.2010	37.2	19.08.2015	42.5
25.07.2010	33.2	13.07.2016	35.2
09.06.2011	94	10.06.2018	49.2
29.07.2012	36.4	23.05.2019	32
24.06.2013	59.6	23.06.2019	91.3
15.10.2013	40.2	13.08.2019	76.8
04.08.2014	32.2	26.06.2020	57.2
10.09.2014	46.7	13.10.2020	46.8

Source: Hungarian Meteorological Service.

tion was practically zero in conventionally tilled fields. In less compacted fields with roots, two orders of magnitude greater infiltration that significantly dampened precipitation events were measured. At sampling sites 3 and 4, the drastic difference in permeability was also influenced by the cultivation technology applied in the area. In the case of meadows, due to the cracks in the marshy soil and the dense root system of soft-stemmed plants, precipitation immediately infiltrates into the deeper layers of the soil, while in the cultivated seedbed, the natural cracking of the soil is worked out, and the drainage capacity is almost zero. This effect is periodic: during wet periods, the soil of the meadow swells with moisture and, similar to the seedbed, it seals. The infiltration data measured at sampling site 5 show that a significant portion of the precipitation infiltrates due to the good water-conducting properties of the soil's coarse physical nature, indicating that the method well reflects the soil's physical nature.

The vegetation improves the soil's water-conducting capacity mainly through its root network, thereby acting as a brake on surface runoff. In the case of forest vegetation, the canopy also retains a significant amount of water before it reaches the soil (Balatonyi, L. 2015). For steep terrain, the amount of precipitation falling in windless weather on a unit area is also less. These results were taken into account in the spatial extension, and the land cover map also explains the variability of the results.

Results and discussion

Results of the model input parameters

The results of land use mapping from the Sentinel 2 satellite imagery are as follows *(Figure 3).* During the supervised classification 8 classes (arable, forest, built-up, etc.) were created, during classification an average accuracy of 98.5 percent and a kappa accuracy value of 97.0 percent were achieved, which metric demonstrates that the individual land cover classes are perfectly separated within the classification model.

The built-up, covered areas account for 3.57 percent of the analyzed catchment, while the uncovered, infiltrating areas make up 96.43 percent. The proportions of the land-use classes obtained from the classification results are summarized in *Table 2*.

Distinct infiltration and runoff characteristics are exhibited by the individual land cover classes. Therefore, the most representative roughness coefficients were assigned to each class: forest = 0.3; pasture = 0.6; arable land = 0.8; built-up area = 1. In the model, by multiplying the velocity with this land cover raster, we obtained the area-specific modified flow velocity. During the modelling process, the previously presented extreme precipitation intensities (see *Table 1*) were utilized as input data, and the individual scenarios were tested. Comparisons were made with the Stowe model, the results of which are discussed in a subsequent chapter.

Results of input soil parameter analysis

Field and laboratory soil measurements are crucial for determining the model input soil parameters and their spatial extension. Laboratory analyses of the samples focused on essential soil physics parameters for accurate parameterization of the hydrological model (soil mechanics, bulk density, etc.). The soil's physical heterogeneity varies with the topography. The occurrence of loose sediments in the area can be linked to the topographic situation. Therefore, when creating maps of physical heterogeneity, the digital elevation model (DEM) and the geological map as auxiliary variables for spatial extension (Universal Co-Kriging interpolation) were used. As the pore conditions and water retention capacity depend strongly on land use, these data were used when creating maps of pore space and measured water drainage capacity. In the temporal modelling of rainfall runoff, we considered pore space and infiltration speed and modified the runoff speed based on land-

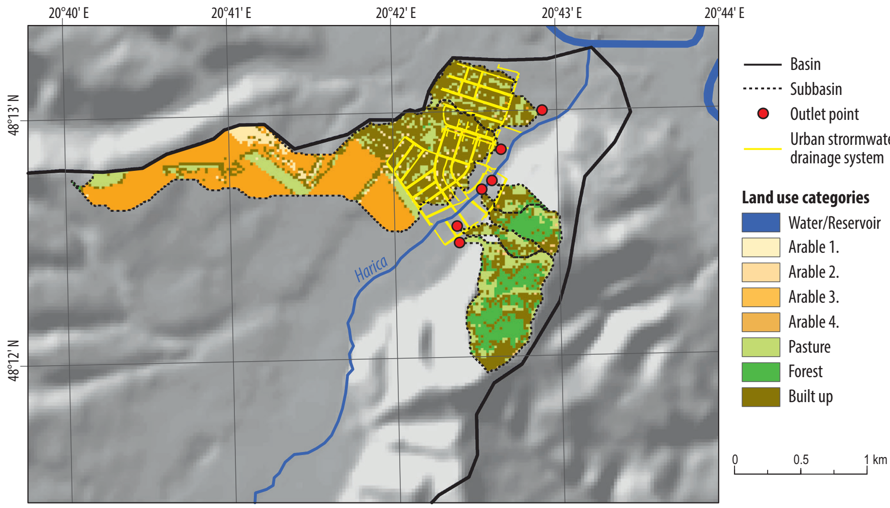

Fig. 3. Land-use map of Harica-Nyögő watershed. *Source:* Elaborated by the authors.

Table 2. Extent and percentage of land-use classes

Land use	Extent, km²	Class percentage, %
Water surface	0.1016	0.128084
Forest	46.9528	59.192060
Pasture	16.4388	20.723930
Arable land 1	0.6592	0.831035
Arable land 2	4.2716	5.385085
Arable land 3	0.2808	0.353997
Arable land 4	7.7824	9.811051
Built-up area	2.8356	3.574760
Total	*79.3228*	*100.000000*
Overall class perf., %	98.5	–
Kappa Statistic (X100), % Kappa Variance	97.0 0.000018	–
Av. likelihood prob., %	38.1.	–

use data. The saturation of the pore space varies depending on the precipitation intensity, the results of which are as follows *(Table 3)*.

Based on the data of the soils sampled and analyzed in the laboratory during the field survey *(Table 4)*, we first mapped the spatial distribution of soil particle sizes, a parameter that well characterizes pore conditions and, thus, water retention capacity.

During the ME-Hydrograph model run, the periodic differences in water saturation can also be considered and adjusted. For this purpose, infiltration rate and capacity values were calculated for the area based on field measurements, extended by the digital elevation model. When designing the model, we multiplied the soil's water absorption capacity by a saturation factor between 0 and 1, which indicates the soil's capacity to absorb water at a given moment. For example, summer-dried soil was assigned to a factor of 0.8, while a winter-frozen soil gets a fac-

Table 3. Results of infiltration measurements

Measure	Amount of water, mm	K_ AVG, mm/s	Infiltrate_ AVG, m	Infiltrate_time, min	Soil type	Land use	Position
Frame 1 (SSZTP_1)	170	0.04	0.08	85	Luvisol	arable land	mid-slope
Frame 2 (SSZTP_1)	180	0.02	0.02	83	Gleysol	arable land	plane
Frame 3 (SSZTP_2)	210	3.12	0.14	10	Luvisol	meadow	slope shoulder
Frame 4 (SSZTP_2)	205	0.01	0.05	136	Luvisol	arable land	slope shoulder
Frame 5 (SSZTP_3)	190	2.11	0.13	10	Luvisol	meadow	hilltop, shoulder

Note: SSZPT = Sajószentpéter.

Table 4. Results of soil sample analysis

Sample ID	Depths, cm	Sand%, 0.05–2 mm	Silt%, 0.002–0.05mm	Clay, < 0.002 mm
SSZTP01/1	0–10	36.7	24.5	38.9
SSZTP01/2	10–25	34.5	24.1	41.3
SSZTP01/3	25–40	33.7	21.8	44.5
SSZTP01/4	40–80	35.6	20.4	44
SSZTP01/5	80–100	36.6	20.7	42.7
SSZTP02/1	0–25	35.28	31.94	32.78
SSZTP02/2	30–50	25.51	25.75	48.74
SSZTP02/3	50–100	23.04	24.45	52.51
SSZTP03/1	0–10	73.29	13.41	13.30
SSZTP03/2	10–30	72.77	11.17	16.06
SSZTP03/3	30–50	86.45	5.37	8.18
SSZTP04/1	0–20	47.92	19.68	32.40
SSZTP04/2	20–55	39.35	20.63	40.02
SSZTP04/3	55–75	38.59	19.04	42.37
SSZTP04/4	75 <	38.97	18.50	42.53

tor of 0.1. In this way, the time it takes for the soil to reach saturation was calculated for each pixel.

If the soil cannot infiltrate because the infiltration rate is lower than the precipitation intensity, the excess appears as runoff discharge. Similarly to the Stowe-Hydrology tool, the time of concentration and velocity elements were integrated into the model as discussed earlier. Adding this time to the runoff time, we get how long it takes for water to flow from the pixel to the outlet point from the start of rainfall, depending on soil quality, land cover, slope, and watershed size. This modified runoff time raster was classified into 10-minute intervals for ease of subsequent calculations and overview (*Figure 4*).

This classified isochrone map shows how many pixels drain water to the outlet point

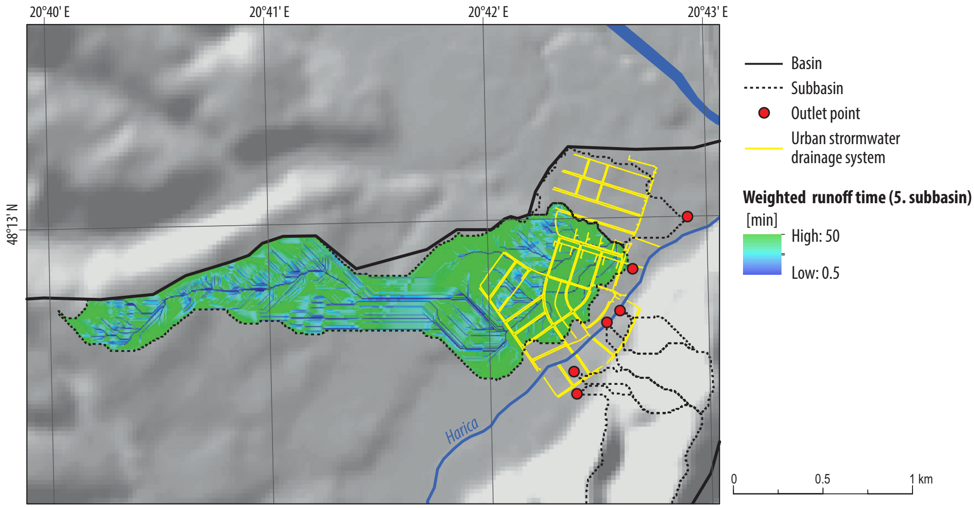

Fig. 4. Weighted runoff raster dataset for 5th outlet point. *Source:* Elaborated by the authors.

in a given 10-minute interval from the start of rainfall. For rainfall events lasting longer than 10 minutes, we had to add the areas of these 10-minute bands from the outlet point to the end of the rainfall duration. When the rain stops, we add any 10-minute bands remaining in the upper part of the watershed, as this water has not yet flowed. At the same time, we subtract the 10-minute bands located downstream, as this water has already left the area.

We then calculated the amounts of water that flowed through the outlet points and their associated times. We multiplied the pixel counts by the pixel area (25 m^2) to obtain the areas in square metres for each 10-minute interval. By dividing the rainfall amount by the rainfall duration, we calculated the rainfall intensity, i.e., the rate of rainfall in mm per second. By graphing these data, we obtained hydrographs, which show how the quantity of water flowing through the outlet point changes over time for a given area, rainfall amount, and rainfall duration. As a result, a dataset weighted by surface properties and soil parameters (including porosity and infiltration rate) was generated and classified into 10-minute intervals *(Figure 5).*

Results of the comparison between the two runoff models

The outflow point 5, which forms the basis of the study, belongs to the largest watershed, covering an area of 1.4 km^2. Consequently, a scenario with 100 mm of precipitation over 240 minutes was examined for this watershed. The results of Stowe-Hydrology tool and ME-Hydrograph were compared (*Figure 6*), during which the peak values were multiplied by 100 to evaluate the discharge results provided by the two hydrographs.

In the hydrograph of the ESRI Stowe-Hydrology tool, it can be observed that at the 220th minute, a flow of 230 m^2/s would reach the outflow point from the contributing area. The flood wave generated by the ME-Hydrogaph model, as shown in *Figure 6*, indicates that there is no significant discharge until the 230th minute because, up to that point, the soil has absorbed most of the water. Around the 230th minute, the curve starts to rise steeply and reaches its peak around the 350th minute when approximately 1700 l/s of water arrives at the discharge point. This delay occurs because it takes this amount of time for water from the upper

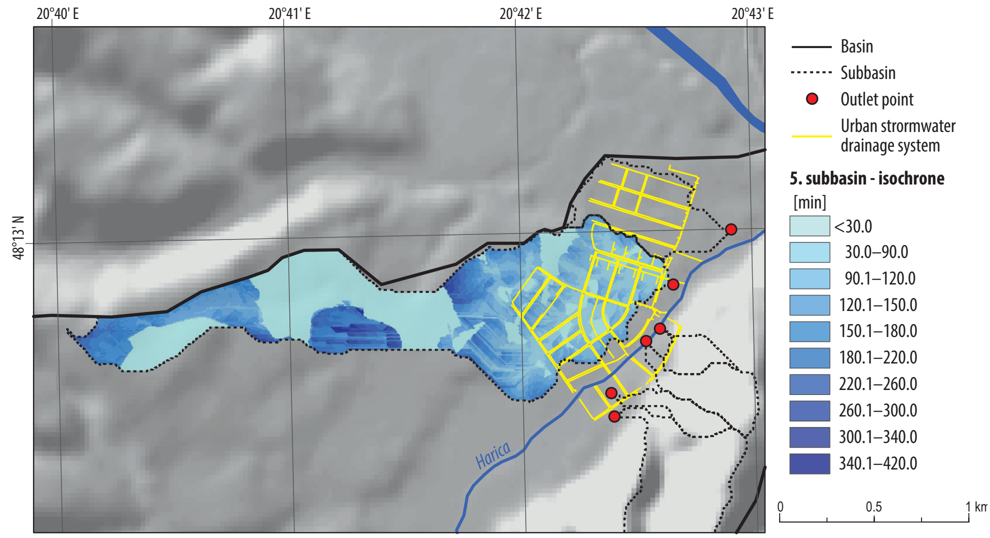

Fig. 5. 10-minute classified isochrone map of 5th outlet point (modified by surface cover and soil factors). *Source:* Elaborated by the authors.

parts of the watershed to reach the outlet. Along the descending branch of the curve, it can be observed that the water runoff from progressively smaller areas is completely exhausted after approximately 660 minutes.

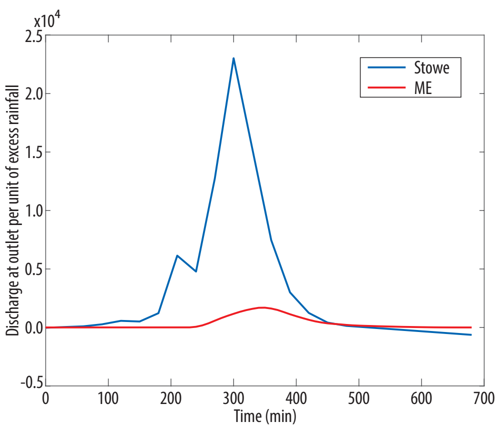

Fig. 6. Result of Simpson's 3/8 rule. *Source:* Elaborated by the authors.

The integration of the area under the two curves was performed using the Simpson's 3/8 method, which is a numerical integration procedure and a variation of Simpson's rule. The basic idea is to approximate the area under a given function using triples corresponding to the function values. The notation 3/8 indicates that the method uses three function values on each subinterval. The 3/8 method can provide more accurate results than the classical Simpson's rule, especially when the function values vary significantly within the integration range (Pandey, K. *et al.* 2011). The results obtained from the traditional trapezoidal integration method and the applied Simpson's rule were almost identical.

The areas under the curves show the amount of water that has flown through the outlet points. As the Y axis of the hydrograph (see *Figure 6*) has a unit of l/s, we have to convert that to l/min to be able to dismiss the min and get liter as the result of the integration of the curve. Thus, the above numbers were multiplied by 60 and then divided by 1000 to get the amount of water in m^3 (Eq 2, *Table 5*).

$$\text{Area under curve in } m^3 = \frac{\text{Integration of the area under curve} \cdot 60}{1000} \ [m^3] \quad (2)$$

The area of the watershed is 1,383,975 m^2. The total amount of rain that has fallen to the area is calculated by multiplying the area of the watershed with the amount of rain, resulting 138,398 m^3 (Eq 3).

$$\text{Total amount of rain} = \text{Watershed } [m^2] \cdot \text{Amount of rain } [m] \ [m^3] \quad (3)$$

One can see that from the total amount of rain (138,398 m^3), only 16,252 m^3 has left through the outlet point, which is 11.7487 percent of the total precipitation, and, thus, 88.2513 percent was retained by the soil *(Table 6).*

We can see about the same percentage if we check the areas under the Stowe and the ME curves. We get 147,646 m^3 as the result of the integration of the Stowe curve and we already know the 16,252 m^3 from the integration of the ME curve. The differences in the results between the two models can be attributed to the soil parameters (infiltration rate, pore space etc.), highlighting the significant retention effect that the initial properties of the soil have, particularly during the first hour of a precipitation event. As the Stowe model does not consider any infiltration, while the ME model does, the ratio between them should show the percentage that has been run off and retained. So, in this case 11.0074 percent of the water ran off and 88.9926 percent was retained by the soil (see *Table 6*). The reason the Stowe model does not match exactly with the total amount of precipitation calculated by the area · amount of precipitation, is that it uses some empirical constants.

The similarity of the percentages confirms that the GIS application developed by ME, models water runoff well by taking into account the water retaining capacity of the soil, thus, providing reliable hydrographs. Such consistency indicates that the method is robust and can yield results.

During the investigation, the model was also tested using rainfall events of varying intensities, with rainfall lasting half as long (50 mm/120 minutes) and twice as long (200 mm/480 minutes) as the previously presented intensity being analyzed. As a result of the first scenario, no water appeared at the outflow point because the water yield had been infiltrated by the soil. Under theoretical conditions of a 200 mm/480-minute rainfall event, around the 230th minute, a significant rise in outflow water was observed, and it was concluded that (similar to previous tests) around the 220th–230th minute, the soils had become saturated. It is important to note that these results strongly depend on the initial soil saturation. The aim of using the precipitation intensities presented in these examples was to validate the importance of initial soil parameters in runoff modelling.

Table 5. Result of Simpson's 3/8 method

Curves	Area under curve	
	from original hydrograph	in m^3 by Eq 2.
Stowe	2,460,772.1454	147,646.3287
ME	270,876.0551	16,252.5633

Table 6. Percentages of runoff and ratained water between the two models

Percentages	ME model/ Actual rain amount	ME model/ Stowe model
Runoff percent, %	11.7487	11.0074
Retained percent, %	88.2513	88.9926

Result of the analysis of the urban stormwater drainage systems capacity

In the research, the capacity of the sewer network was also examined. The water-carrying capacity data for the sewer network were obtained from the submitted permitting documentation. The runoff quantities assigned to the endpoints were compared with the water conveyance capacity of these endpoints' sewer systems. The sewer network and watershed areas were grouped, and the water yields for each corresponding watershed were aggregated along with the discharge capacities of the sewer networks covering those areas.

In the ME-Hydrograph model, we examined when the runoff of the combined watersheds reaches the drainage capacity of the corresponding sewer network. For individual watershed areas and watershed area groups, we calculated the maximum runoff values for various precipitation intensities and durations, as mentioned above *(Table 7).*

The data indicates the number of minutes for these flow values to reach the drainage capacity of the channel unit associated with the catchment area. In the vicinity of the area (Putnok), the maximum daily precipitation measured so far is 100 mm, so the occurrence of significantly larger rainfall is unlikely. The rightmost column shows the duration required to reach 100 mm of precipitation for the respective intensity values. It can be seen that the time required to reach 100 mm of rain is less than the time required to reach the threshold for each precipitation intensity. Accordingly, if rainfall exceeding the observations to date does not occur, the sewer network is capable of draining the runoff from the surrounding areas.

Conclusions

The results underline the importance of precise hydrological modelling to better understand and mitigate the impacts of intensive rainfall events.

By examining the methodologies and results of runoff models in other studies, it can generally be stated that, despite their wide applicability, the integration of remote sensing data (Courty, L. G. *et al.* 2017) and the opportunities provided by soil databases (Poortinga, A. *et al.* 2017; Shuli, W. *et al.* 2024) have not yet been incorporated into runoff models. Furthermore, in most cases, due to the absence of reliable precipitation forecasts, significant uncertainties are associated with the calculation of water discharge on so-called ultra-small hydrologically unexplored catchments. These uncertainties affect the determination of floodwave magnitudes impacting urban areas, as multiple sub-catchments may surround a settlement. In such cases, distributed hydrodynamic models are developed, and input data requirements are significantly increased (Hongping, Z. *et al.* 2021). Without these data, the assessment of sewer network loads caused by floodwaves, as well as the development of flood risk mapping methodologies, cannot be achieved.

The newly developed ME-Hydrograph model, alongside its GIS integration, has proven to be a reliable tool for evaluating surface runoff dynamics and assessing urban drainage system capacities. By incorporating detailed soil water absorption properties and calibrated boundary conditions, the model has achieved a high level of accuracy. To achieve the objectives of the study, several key actions were undertaken. First, boundary conditions were optimized using a combination of archive and field data, ensuring that the

*Table 7. Maximum water flow values for different rainfall scenarios**

Precipitation intensity, mm/h	Amount of time to reach				Number of minutes it takes for the rain to reach, 100 mm
	1. + 2.	3. + 4.	5.	6.	
	catchment limit value, min				
5	cannot reach	cannot reach	cannot reach	cannot reach	1200
10	800	cannot reach	810	cannot reach	600
15	530	cannot reach	540	520	400
20	420	420	410	390	300
25	330	330	330	310	240
30	280	280	280	270	200
40	210	210	210	210	150
50	170	170	170	170	120
Drainage capacity max., l/s	1194	754	2845	705	–

*Intensities and durations.

model accurately reflects local hydrological dynamics. Next, the land use and soil properties of the affected small watersheds were meticulously mapped, providing essential input data for runoff calculations. A general assessment of the soil and its infiltration characteristics across the watershed was also conducted, with infiltration rates estimated at representative points to capture spatial variability.

Building on this foundation, an existing runoff model, Stowe-Hydrograph, was refined and enhanced by incorporating the gathered data, culminating in the development of a new, more complex runoff model, ME-Hydrograph. This advanced model was designed to better simulate water movement and retention dynamics within the target area. Finally, the models were compared, and the load capacity of the existing drainage system was assessed based on the permitting plan, offering valuable insights into the system's ability to manage runoff under varying conditions. The similarity of the percentages of runoff and retained water confirms that the GIS application developed by ME effectively models water runoff by accurately considering the soil's water absorption capacity. This results in reliable hydrographs that closely reflect real-world conditions. The consistency of the outcomes demonstrates the robustness of the method, highlighting its ability to produce dependable and reproducible results across varying scenarios.

During the drainage system load capacity assessment, it was determined that, considering the maximum precipitation load, the urban sewer network of Sajószentpéter is capable of draining the surface runoff from the surrounding catchment areas. This has been confirmed based on several different precipitation event scenarios. However, several factors (e.g. implementation of additional surface, land use properties and consideration of linear infrastructure) have not yet been included in the model, which will be subjects of future research.

The future of the ME-Hydrograph is primarily characterized by the integration of machine learning algorithms. However, due to the inherent non-linear nature of these methods, their application is possible only when supported by robust theoretical foundations (Jehanzaib, M. *et al.* 2022). While the increased data demands associated with soil surface characteristics pose challenges, the implementation of NDVI and other indices has initiated this progression, offering a potential framework to guide future research efforts (Gupta, A. *et al.* 2024; Shuli, W. *et al.* 2024). In this context, significant potential lies in the integration and connection of the region's digital soil map (E-Soter soil database) with the research, enabling its application to larger-scale catchments (Dobos, E. *et al.* 2007). Nevertheless, in parallel with the development of runoff modelling, the enhancement of flood risk mapping methodologies remains essential to ensure proper validation.

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New realities of the administrative-territorial structure of Ukraine and areas of ethnic minorities' settlement: Geographical correlations and social consequences

Examples of Zakarpattia, Chernivtsi and Odesa oblasts

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Abstract

This article analyses the ethno-geographical problems of the reformed system of administrative and territorial structure of Ukraine. The authors consider the alignment of newly created administrative units (rayons, territorial communities) and areas of compact settlement of ethnic minorities as a favourable prerequisite for the organisation of local self-government and the establishment of balanced and mutually beneficial ethno-political relations in the state. The analysis of the ethno-geographical parameters of ethnic minorities and the configuration of the newly created administrative-territorial units revealed that the population of ethnic minorities in Zakarpattia, Chernivtsi and Odesa oblasts was given the opportunity to organise territorial communities in which they constitute the majority. At the same time, studies have shown that it was not easy to implement this approach in the newly created administrative districts, given the officially defined criteria, the politicisation of the issue and the relatively high degree of mosaic settlement of ethnic groups. Therefore, the ethno-geographical factor was only partially taken into account in the formation of new administrative districts and the selection of district centres.

Keywords: administrative and territorial reform, ethnic minorities, settlements, local self-government, territorial communities, Ukraine

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Introduction

In recent years, since 2014, events in Ukraine have attracted the attention of both the media and academia, including geographers. A change in the frequency of its appearance in the English-language literature can be indicative of the popularity of a particular topic (Van der Wusten, H. 2015). A search of the N-gram viewer revealed that the name "Ukraine" was referenced in an average of 8.2 publications per million books published in English in 2015. This figure represents a notable increase from 2012, when the average was 4.7 (see books.google.com/ngrams 2024). It is evident that the primary focus of this study is on events and processes related to the Russian-Ukrainian war (e.g. Karácsonyi, D. *et al.* 2014; Dobysh, M. 2019; Gnatiuk, O. *et al.* 2022). However, it is important to note that other problematic issues of a geographical nature remain in the country, including the issue of ethnic minorities living compactly in the western regions of Ukraine.

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Ethnic minorities in Ukraine comprise all population groups that do not identify with the Ukrainian ethnicity. This includes small indigenous peoples (Crimean Tatars, Karaites, Gagauzes) and ethnic groups that are part of peoples whose main core resides outside Ukraine (Belarusians, Bulgarians, Poles, Hungarians, Romanians, and some others). The gradual democratization of European countries' political systems, including the principle of respect for the rights and interests of ethnic minorities, has allowed for the development of mechanisms to coordinate their interests with those of states and dominant ethnic groups. One of the tools for harmonizing opposing interests is precisely the administrative-territorial system (Makarov, H. 2022, 56). Consequently, the ethno-geographical characteristics of numerous countries worldwide are considered to varying extent in their administrative and territorial frameworks.

As a result of the 2015–2020 administrative-territorial reform in Ukraine, aimed at giving more powers to local self-governments, significant changes have taken place at the lower and middle levels of the administrative-territorial system. At the lower level, instead of more than 11,000 village, town and city councils, 1470 territorial communities were created, and instead of 490 rayons, 136 new ones were formed (see www.kmu.gov.ua, 2020). Obviously, such significant changes, disrupting already established ties, could not but affect various aspects of the life of the local population, including ethnic minorities. Therefore, to ensure ethno-political balance and stability, it is advisable to find out whether the new administrative-territorial system has taken into account the peculiarities of compact settlement of ethno-national minorities.

Reflecting the problem in scientific literature

The multidimensional issue of the administrative structure of the state territory is studied by more than two dozen scientific fields, including political and legal sciences, history, political science, sociology, and management. Geographical science is also involved in the comprehensive study of the administrative-territorial structure, and it has become the subject of a separate branch of study, administrative geography (Hajdú, Z. 2014, 33). Administrative geography focuses primarily on optimizing the territorial organization of countries, the configuration and size of administrative units.

As for optimization, there are still many unsolved issues. For example, there is no perfect answer to the question of the optimal size of administrative units which would ensure both local democracy and economic efficiency in the delivery of local public services. Different solutions are implemented in order to reach this goal (CEMR 2009, 5). This is also the problem of applying the ethnic principle in determining the boundaries of administrative units.

In today's world there is a clear understanding of the need to ensure the civil rights of ethnic (national) minorities (political, cultural, religious, etc.), as evidenced by the adoption of a number of international legal documents, but at the same time there are no unified approaches to reflecting their interests in the systems of territorial organisation of state power and local self-government. This is mainly due to the diversity of options for the states' ethnic structure. Therefore, most of them have developed their own strategic political and administrative approaches to addressing such issues, based on national legal documents.

Some authors believe that ethnic minorities within administrative units have three options: assimilation, emigration or mobilisation of forces to create their own administrative units (Müller-Crepon, C. 2023). This may seem rather categorical, but the creation of more or less mono-ethnic administrative units undoubtedly helps to meet the social, cultural, economic, etc. needs of ethnic communities.

The options for meeting the needs of ethnic minorities are grouped, on the one hand, into various forms of autonomy (territorial, cultural, personal), and, on the other hand, within the administrative system of a unitary state. Best practices – such as the Belgian, Finnish and Italian models – provide for the establishment of certain territorial self-government structures for ethnic minorities (Fodor, Gy. 2010). Although the needs of densely populated ethnic minorities are occasionally expressed, these models are not yet widespread in Central and Eastern Europe. At the same time, such initiatives raise fears and do not find support from government agencies and political forces of the state-forming nations (Mezei, I. and Hardi, T. 2003, 131–134; Szilágyi, F. 2010; Hajdú, Z. 2014, 34; Korzeniewska-Wiszniewska, M. 2020). In the end, the administrative system is largely the product of a kind of compromise, bargaining between stakeholders, rather than a fully science-based system (Osoian, I. *et al.* 2010, 108).

Given the importance of national and state practice, it is important to first analyse how Ukrainian analysts approach this issue, taking into account the interdisciplinary nature of the issue, which has socio-geographical, geopolitical, political, legal and economic aspects. Discussions on this issue since 1991 have stimulated demands from some ethnic minority NGOs for the creation of autonomous national districts (rayons). However, only a few Ukrainian scholars (Baranchuk, V. 1998; Druziuk, S. 1998; Fedchyshyn, M. and Fronchko, V. 2000; Kuchabskyi, O.G. 2010) allowed for the possibility of creating such administrative units, while most other ethno-political scientists and public administration specialists focused on the priority of the extra-territorial form of ethno-cultural autonomy. Suggestions were also made on the possibility of changing the boundaries of administrative units to meet the needs of ethnic minorities (Dnistrianskyi, M.S. 2006) and on the importance of taking the ethnic factor into account in subsequent administrative and territorial changes (Nadolishnii, P. 1999).

In the process of reforming the administrative-territorial structure, which began in 2015, the need to take into account ethnogeographical features was also emphasised at the scientific level (Mustafaieva, E. 2018; Zablotskyi, V. 2021), but without identifying real mechanisms. At the same time, more specific discussions on these issues were held at the level of government agencies, NGOs and, to some extent, interstate relations.

Structural administrative-territorial changes in general (consolidation of administrative rayons, increase in the size of the smallest administrative units, reduction in the administrative status of settlements) have also affected the livelihoods of ethnic minority populations, resulting in a significant increase in the distance to new administrative centres and, consequently, a number of other socio-economic problems. Skliarska, O.I. claims “In today’s conditions, most rural communities cannot take advantage of decentralisation opportunities due to the limited socio-economic potential of settlements, including large villages that have become community centres” (Skliarska, O.I. 2022). The issue of economic and demographic capacity of municipalities is topical. According to domestic and foreign experience, in the case of rural municipalities it is mainly ensured only in suburban agglomerations (Skryzhevska, Y. and Karácsonyi, D. 2012; Hruška, V. and Píša, J. 2019). These issues, namely various aspects of the conformity of the new administrative-territorial division and the resettlement of the population of Ukraine in general, have been widely reflected in other publications, in particular in the works of Zastavetska, L.B. (2013), Baranovskyi, M.O. (2017, 2020), Kuchabskyi, O.G. *et al.* (2017), Melnychuk, A.L. (2020), Savchuk, I. (2020), Skliarska, O.I. (2021), Dnistrianskyi, M.S. and Chaika, I.M. (2023), and others. The analysis of the issues raised in these publications is indirectly related to the social situation of ethnic minorities.

Research objectives and methodology

This study examines the compliance of Ukraine’s reformed administrative-territorial structure with the settlement of ethnic minorities. It considers three oblasts that share common typological features of ethnic minorities' settlement and are characterised by large areas with a predominant majority of ethnic minority population: Zakarpattia, Odesa and Chernivtsi. Based on the nature of the problem, the main objectives of this study are 1) to analyse the level of density and mosaicism of ethnic minority settlements in Zakarpattia, Chernivtsi and Odesa oblasts; 2) to determine the correlation between the middle and lower levels of the reformed administrative-territorial division of Ukraine and the areas of settlement of ethnic minorities; 3) to objectively analyse the improvement of the compliance of newly created administrative units (territorial communities) with the areas of settlement of ethnic minorities; 4) to substantiate conceptual conclusions on the possibilities of reflecting the geography of ethnic minorities in the administrative and territorial division of Ukraine.

The main problem in the implementation of the research tasks is the limited source base on the current ethno-national structure of Ukraine's population, given that the last census in Ukraine took place in 2001. However, there is no alternative to using the materials of this census, as there have been no fundamental changes in the areas of compact settlement of ethnic minorities since then, with the exception of the territories not controlled by Ukraine since 2014, where no reform has been carried out.

The theoretical framework of the study is based on the following principles:

1. Ensuring closer correspondence between the units of the administrative-territorial structure and the areas of compact settlement of ethnic minorities, creating better conditions for the organisation of their local self-government, is the key to establish balanced and mutually beneficial ethno-political relations in the country.

2. The establishment of administrative-territorial units at varying levels, in alignment with the geographical distribution of ethnic minorities is not a prerequisite for ethno-political separatism. Rather, it serves as a foundation for developing constructive and trusting relations between ethnic minorities and the country as a whole.

3. The formation of new territorial communities in areas of ethnic minority settlement should be based on the coordination of the local citizens' positions and public interests.

The methodological basis of the study is a structural-functional approach and a regional-comparative analysis of the location of administrative-territorial units, their centres and settlements with a significant share of ethnic minorities, as well as determination of the real correlations that existed before and after the reform.

A comparative analysis of the ethnic composition of the old and new administrative units gives rise to the question of which rank of units from the previous and current divisions should be compared. The answer is that the units are of the same rank, but they are also significantly different in size (the new ones are much larger). The choice for comparison fell on rayons of the previous administrative structure and territorial communities of the new one, since territorial communities have become the most functionally significant administrative units in the organisation of local self-government, replacing the former rayons. Territorial communities, in compliance with the reform, were given significant powers to form local budgets and internal socio-economic policies. At the same time, the powers of rayons in general and rayon councils in particular have not yet been conceptually developed.

These methodological approaches were implemented through the use of the cartographic method, as well as methods of analysing the distribution of ethnic minority areas, ethnic and settlement mosaic of administrative districts and territorial communities.

The analysis of the proportion of ethno-linguistic minorities in the former rayons is also of fundamental importance in assessing the conformity of the newly created administrative units with ethno-geographical realities. To quantify the ethno-geographic structure in each of these three regions, we also calculated an indicator of ethno-linguistic mosaicism, which takes into account the proportions of language groups, and linguo-settlement mosaicism, which is the diversity of the distribution of settlements with a majority of a particular ethno-linguistic group in terms of rayons and newly created territorial communities as of 2001. The classical index of ethnolinguistic mosaicism is calculated according to the formula (Mruchkovskyi, P.V. 2018; Németh, Á. 2019):

$$E = 1 - \sum_{j=1}^{k} (\varepsilon_j^{\,2}),$$

where E is the index of ethnolinguistic mosaicism, ε_j is the share of the population of the j-th language group in the administrative unit, k is the number of ethnolinguistic groups. The index of linguo-settlement mosaicism is determined by the formula:

$$P = 1 - \sum_{j=1}^{k} (\pi_j^{\,2}),$$

where P is the index of language-settlement mosaicism, π_j is the share of settlements with a majority population of the j-th language group among the settlements of the administrative unit, k is the number of ethno-linguistic groups.

Summary of research findings

Prerequisites for the reform

Independent Ukraine inherited the foundations of its administrative and territorial system from the Ukrainian SSR. In 1991, 24 oblasts, the Crimean Autonomy, the cities of Kyiv and Sevastopol formed its upper tier, 481 rayons, and 147 cities of Oblast significance formed its middle tier, and 287 rayon councils, 925 settlement councils and 9211 village councils formed its lower tier. The gradual shift away from totalitarianism and the democratisation of society have also led to various proposals to change this system and the emergence of practical initiatives to create new administrative units. As a result of these trends, nine new administrative rayons were created at the middle tier between 1991 and 1996, bringing the number of rayons to 490. One of them, the Hertsa Rayon of Chernivtsi Oblast, was created in December 1991 on the initiative of the Romanian ethnic minority (Dnistrianskyi, M.S. 2006). At the same time, the decision of the 1991 local referendum on the creation of Berehove Hungarian (Zakarpattia Oblast) and Bulgarian (Odesa Oblast) national rayons was not officially approved, as there was no appropriate legal framework for such a decision.

The main ethno-geographic features of independent Ukraine were recorded in the first and only all-Ukrainian population census in 2001. According to its findings, ethnic minorities made up 22.2 percent of the total population of Ukraine, 26.3 percent of the urban population, and 12.9 percent of the rural population. At the time, the majority of ethnic minorities were concentrated in large cities, as shown by the regional proportions of ethnic minorities in rural and urban population.

The largest share of ethnic minorities was in the following regions: Sevastopol City (77.6%), the Autonomous Republic of Crimea (75.7%), Donetsk (43.1%), Luhansk (42.0%), Odesa (37.2%), Kharkiv (29.3%), Zaporizhzhia (29.2%), Chernivtsi (25.0%), Dnipropetrovsk (20.1%), Zakarpattia (19.5%), Mykolaiv (18.1%), and Kherson (18.0%) oblasts. Thus, at the upper tier of Ukraine's administrative and territorial structure, only one region, the Autonomous Republic of Crimea, and the city of national significance Sevastopol, had a predominantly non-Ukrainian population. This ethno-geographical feature in these regions was reflected in the administrative-territorial system of Ukraine by granting them special status. Out of the above regions, only Zakarpattia, Chernivtsi and the south-western part of Odesa Oblast have areas where several ethnolinguistic groups are settled, and therefore they have been chosen as the object of our study.

The administrative-territorial reform in Ukraine was initiated in 2015 with the objective of conferring greater autonomy upon local self-governments. Its implementation was preceded by the adoption of such documents as the Law of Ukraine on Voluntary Amalgamation of Territorial Communities (2015), and the Decree on Approval of the Methodology for the Formation of Capable Territorial Communities (2015), which defined the procedure and main criteria for the formation of new administrative units (in terms of the size of new administrative units, location of centres, etc.). Among the principles to be taken into account, the law also mentioned ethnicity (see zakon.rada.gov.ua/laws/show/214-2015-%D0%BF#n10, 2015), but the mechanisms for implementing this principle were not specified.

Until 2020, the formation of territorial communities was voluntary, which allowed residents belonging to ethnic minorities to amalgamate into territorial communities in their places of compact settlement. By that time, 1070 communities had been formed (almost 73%). Moreover, the following communities were formed according to the perspective plans developed at the governmental level (www.kmu.gov.ua, 2020).

The consolidated communities were endowed with considerable powers and resources, including revenues derived from taxes, such as a unified tax, taxes on the profits of municipal-owned enterprises and financial institutions, property (real estate, land, transportation), and 60 percent of personal income tax, which were transferred to local budgets. Before the reform, only oblast, rayon budgets and budgets of cities of oblast significance had direct relations with the state budget. Following the reform, territorial communities (TCs) have direct inter-budgetary relations with the state budget. Appropriate transfers (grants, subventions, etc.) are received by TCs to enable them to perform their delegated powers (www.kmu.gov.ua, 2020). Consequently, territorial communities have become a key element of Ukraine's new administrative structure, which justifies the emphasis placed on them in our investigation.

In order to examine the extent to which the reformed system of administrative and territorial structure of Ukraine complies with the settlement of ethno-linguistic minorities, a case study was conducted in Zakarpattia, Odesa and Chernivtsi oblasts since in other regions where the reform was implemented, there are actually no relatively large areas where ethnic minorities would form the majority.

Thus, the results of the census show that the share of ethno-linguistic minorities and the share of settlements with a majority of ethno-linguistic minority population were the highest 1) in Hertsa Rayon of Chernivtsi Oblast (91.5% of ethnic Romanians, 92.2% of the population named Romanian as their mother tongue, the share of settlements with a predominance of Romanian-speaking population is 95.5%); 2) in Berehove Rayon of Zakarpattia Oblast (76.1% of ethnic Hungarians, 80.2% of the population named Hungarian as their mother tongue, the share of settlements with a predominance of Hungarian-speaking population is 76.7%); 3) in Bolhrad Rayon of Odesa Oblast (60.8% of ethnic Bulgarians, Bulgarian was the mother tongue of 57.5% of the population, the share of settlements with a predominance of the population with the Bulgarian language as their mother tongue was 59.1%). In addition, the degree of compactness of ethno-linguistic minorities was relatively high in the former Uzhhorod, Vynohradiv and Tyachiv rayons of Zakarpattia Oblast, as well as in Novoselytsia and Storozhynets rayons of Chernivtsi Oblast. In other rayons, these indicators were much lower, which objectively did not contribute to the creation of ethnically homogeneous territorial communities.

Difficulties in taking into account the ethno-geographical factor in reforming the administrative-territorial structure in Zakarpattia, Chernivtsi and south-western Odesa oblasts are also reflected in the indicators of language and language-settlement mosaicism, which were significant in virtually all rayons, including those with the highest proportion of ethno-linguistic minorities. This is especially true in the south-western part of Odesa Oblast (historical Budzhak region), where settlements with different ethnic majority are highly dispersed and the degree of compactness of ethnic minority areas is low. It is noteworthy that in most rayons the overall indicator of linguistic mosaicism was higher than that of linguo-settlement mosaicism, which also reveals the tendency to "blur" the areas of compact settlement of ethnolinguistic groups in the process of urbanisation and migration (see *Tables 1–3).*

Conformity of the newly formed administrative-territorial units and areas of ethnic minorities' settlement in Zakarpattia Oblast

Let us first consider the results of the administrative reform of Zakarpattia Oblast in the light of interethnic relations policy. The main administrative-territorial changes in this region concerned the liquidation of 13 rayons (Berehove, Velykyi Bereznyi, Vynohradiv, Volovets, Irshava, Mizhhirya, Mukachevo, Perechyn, Rakhiv, Svalyava, Tyachiv, Uzhhorod, Khust) and the creation of 6 new ones (Berehove, Mukachevo, Rakhiv, Tyachiv, Uzhhorod, Khust *(Table 1, Figure 1).* At the lowest tier, the liquidation of 337 city, town and village councils resulted in the creation of 64 territorial communities.

In ethno-geographical terms, Zakarpattia Oblast is distinguished by the compact location of only two ethnic minorities – Hungarian and Romanian. In 2001, the majority of the Hungarian-speaking population lived in Berehove and the urban settlements of Batiovo and Vylok. Their share was also significant in the town of Chop and the urban-type settlement of Vyshkovo – over 40 percent. Most of the villages where Hungarians constituted the majority (31 settlements) in 2001 were located in Berehove Rayon. In the former Vynohradiv Rayon, the ethnic Hungarian majority is recorded in 19 villages, in Uzhhorod Rayon – in 22 villages, and in Mukachevo Rayon – in 6 villages (see pop-stat.mashke.org 2024).

According to the 2001 census, Romanian was declared as a mother tongue by the majority in the urban-type settlement of Solotvyno in Tyachiv Rayon, as well as in 5 villages of the former Tyachiv Rayon and 4 villages of Rakhiv Rayon (see pop-stat.mashke.org 2024).

As the reform will result in territorial communities being the most functionally significant administrative-territorial units in the organisation of local self-government, it is important to consider their structural features in places where Hungarian and Romanian ethnic minorities are densely populated. In this light, it is important to focus on how ethnically homogeneous the newly formed communities are and which settlements are community centres in terms of their organisational and human resources. It is also important to note that the formation of territorial communities was largely voluntary, allowing the local population to make a choice that would meet their interests.

Thus, the Hungarian-speaking population predominates in 7 of the 10 newly established settlements of Berehove Rayon (Berehove, Batiovo, Vylok, Velyki Berehy, Velyka Byihan, Kosyno, Pyiterfolvo) (see *Figure 1*). At the same time, the quantitative predominance of the Hungarian population within the first four municipalities of the rayon is less pronounced due to the diffuse nature of the settlement, with Ukrainian villages being located in areas dominated by ethnic Hungarians and Hungarian villages being located in areas dominated by ethnic Ukrainians.

In the newly created Uzhhorod Rayon, three communities – Chop, Velyka Dobron, and Siurte – are predominantly ethnically Hungarian. Some ethnically Hungarian villages of the former Mukachevo Rayon (Barkasovo, Chomonyn, Serne) were incorporated into Batyovo and Velyka Dobron municipalities with a predominantly Hungarian population, while others (Dertsen, Zhniatyno, Fornosh) – due to their distance from the centres of the Hungarian municipalities and possibly due to other political considerations of the village leaders – were incorporated into territorial municipalities with a majority ethnic Ukrainian population.

*Table 1. Some indicators of the settlement of ethno-linguistic minorities in Zakarpattia Oblast by rayons before the 2020 administrative reform**

Administrative rayons and cities of regional significance (before 2020)	Share of population with Hungarian mother tongue, %	Share of population with Romanian mother tongue, %	Share of settlements with a Hungarian-speaking majority in the total number of settlements, %	Share of settlements with a Romanian-speaking majority in the total number of settlements, %	Index of linguistic mosaicism of former rayons	Index of linguo-settlement mosaicism of former rayons	Average index of linguistic mosaicism of territorial communities of former rayons	Average index of linguo-settlement mosaicism of territorial communities of former rayons	Percentage difference between the indices of linguistic mosaicism of former rayons and territorial communities	Percentage difference between the indices of linguo-settlement mosaicism of former rayons and territorial communities
Berehove	80.2	0.0	76.7	0.0	0.321	0.357	0.394	0.310	22.4	-13.2
Velykyi Bereznyi	0.1	0.0	0.0	0.0	0.020	0.000	0.021	0.000	3.3	0.0
Vynohradiv	26.3	0.0	40.0	0.0	0.412	0.480	0.227	0.112	-45.0	-76.6
Volovets	0.1	0.0	0.0	0.0	0.018	0.000	0.017	0.000	-4.4	0.0
Irshava	0.1	0.0	0.0	0.0	0.020	0.000	0.020	0.000	-0.2	0.0
Mizhhiria	0.0	0.0	0.0	0.0	0.014	0.000	0.015	0.000	4.1	0.0
Mukachevo	13.8	0.0	6.8	0.0	0.272	0.127	0.267	0.141	-2.0	10.7
Perechyn	0.2	0.9	0.0	0.0	0.067	0.000	0.060	0.000	-9.5	0.0
Rakhiv	2.5	11.5	0.0	12.5	0.270	0.219	0.101	0.080	-62.8	-63.6
Svaliava	0.5	0.0	0.0	0.0	0.053	0.000	0.049	0.000	-7.4	0.0
Tiachiv	2.8	12.4	0.0	9.8	0.287	0.177	0.091	0.000	-68.3	-100.0
Uzhhorod	35.4	0.0	34.8	0.0	0.499	0.454	0.344	0.099	-31.0	-78.3
Khust	3.9	0.0	0.0	0.0	0.092	0.000	0.103	0.000	11.7	0.0
Uzhhorod	7.0	0.1	0.0	0.0	0.393	0.000	–	–	–	–
Berehove	54.8	0.0	50.0	0.0	0.552	0.500	–	–	–	–
Mukachevo	9.6	0.0	0.0	0.0	0.389	0.000	–	–	–	–
Khust	4.3	0.0	0.0	0.0	0.170	0.000	–	–	–	–
Average for the oblast	*12.8*	*2.6*	*13.7*	*1.6*	*0.255*	*0.145*	*0.175*	*0.072*	*-31.7*	*-50.7*

*Calculated by the authors based on the data of the 2001 All-Ukrainian Population Census.

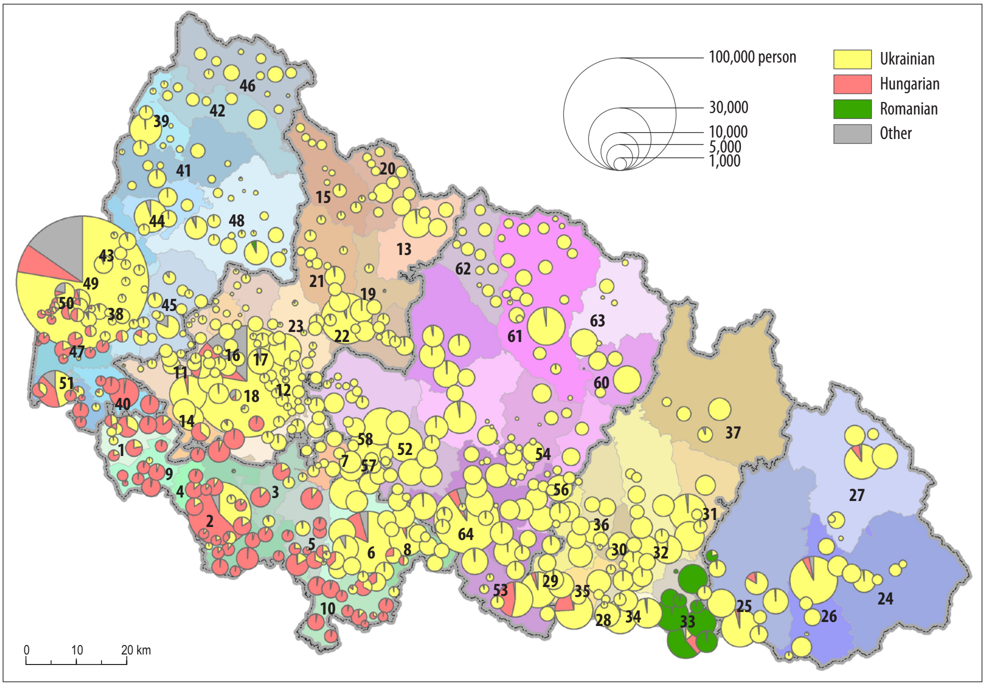

Fig. 1. The composition of the population of the settlements by native language of rayons and territorial communities of Zakarpattia Oblast formed as a result of the 2020 administrative reform. Territorial communities (1–64) of the newly created rayons: **I.** Berehove Rayon: 1 = Batiovo; 2 = Berehove, 3 = Velyki Berehy; 4 = Velyka Byihan; 5 = Vylok; 6 = Vynohradiv; 7 = Kamianske; 8 = Korolevo; 9 = Kosino; 10 = Pyiterfolvo. **II.** Mukachevo Rayon: 11 = Velyki Luchky; 12 =Verkhnii Koropets; 13 = Volovets; 14 = Horonda; 15 = Zhdenievo; 16 = Ivanivtsi; 17 = Kolchyno; 18 = Mukachevo; 19 = Nelipyno; 20 = Nyzhni Vorota; 21 = Poliana; 22 = Svaliava; 23 = Chynadiiovo. **III.** Rakhiv Rayon: 24 = Bohdan; 25 = Velykyi Bychkiv; 26 = Rakhiv; 27 = Yasinia. **IV.** Tiachiv Rayon: 28 = Bedevlia, 29 = Bushtyno; 30 = Vilkhivtsi; 31 = Dubove; 32 = Neresnytsa; 33 = Solotvyno; 34 = Teresva; 35 = Tiachiv; 36 = Uhlia; 37 = Ust-Chorna. **V.** Uzhhorod Rayon: 38 = Baranyntsi; 39 = Velykyi Bereznyi; 40 = Velyka Dobron; 41 = Dubrynychi-Malyi Bereznyi; 42 = Kostrino; 43 = Onokivtsi; 44 = Perechyn; 45 = Serednia; 46 = Stavne; 47 = Siurte; 48 = Turi Remeti; 49 = Uzhhorod; 50 = Kholmok; 51 = Chop. **VI.** Khust Rayon: 52 = Bilky; 53 = Vyshkovo; 54 = Horinchovo; 55 = Dovhe; 56 = Drahovo; 57 = Zarichchia; 58 = Irshava; 59 = Keretsky; 60 = Kolochava; 61 = Mizhhirla; 62 = Pylypets¸63 = Synevyr; 64 = Khust. Based on the results of the 2001 All-Ukrainian Census. *Source*: pop-stat.mashke.org/ukraine-census-2001-lang/zakarpatska.htm 2024.

At the same time, ethnically Romanian settlements in Zakarpattia Oblast, with the exception of the village of Plaiuts, which were previously part of both Rakhiv and Tyachiv rayons, now form one Solotvyno community, which is fully in line with their wishes. Since the formation of territorial communities has been largely voluntary, it has generally created favourable conditions for access to new centres, which now have more grounds to become larger centres of socio-economic development. At the same time, distances to new centres have increased, and a number of settlements have lost the status of village council centres, which in many cases is perceived negatively by the local population.

The consideration of the linguistic and ethnic principle in the formation of territorial communities is reflected in a significant decrease in the average index of linguo-settlement mosaicism per community compared to similar indicators for rayons by 2020. The corresponding indices calculated on the basis of the 2001 All-Ukrainian Population Census data at the oblast level were 0.327 and 0.264. By comparison, the indices for ethnic and settlement mosaicism were 0.337 and 0.254, i.e. the difference was insignificant and is mainly due to the significant proportion of Gypsies (Roma) who use the language of the local majority, mainly Hungarian or Ukrainian, as their mother tongue. As noted above, we chose to use language data because it is more readily available through settlement.

The weighted average index of linguistic mosaicism in the old rayons of Zakarpattia Oblast, according to population, was 0.255, and the index of linguistic settlement was 0.145, i.e. at the rayon level the indices were 21.8 and 44.8 percent lower, respectively. The creation of smaller territorial communities in terms of size and population objectively contributes to the reduction of linguistic and ethnic diversity within them. In Zakarpattia, the average index of linguistic mosaicism for territorial communities was 0.175, which is 31.7 percent lower than the average for rayons. Weighted by the number of population average indicator of linguo-settlement mosaicism decreased even more, by 50.7 percent to 0.072, during the transition to territorial communities, which also confirms the consideration of the linguistic and ethnic factor in the formation of communities in the oblast.

However, the latter statement may be questioned since, as noted above, the reduction in the size of administrative units itself contributes to a reduction in linguistic and settlement mosaicism. In order to clarify the role of the ethnic factor, a hypothetical merger of settlements in Uzhhorod Rayon (a typical multi-ethnic district was chosen) into communities was carried out, taking into account only the territorial principle. The settlements were merged using cluster analysis based on their geographical coordinates (hierarchical cluster analysis, measure – Squared Euclidean Distance, method – between-groups linkage), without taking into account ethno-linguistic composition. The settlements of Uzhhorod Rayon were grouped into 7 communities (according to their actual number). The average weighted index of linguistic and settlement mosaicism decreased to only 0.313, i.e. by 31.1 percent compared to the corresponding indicator of the rayon. In reality, the linguistic and settlement mosaicism in the transition to communities decreased much more radically, to 0.099, i.e. by 78.3 percent (see *Table 1*), emphasizing the role of the ethnolinguistic factor in the formation of communities.

Changes in the indices of linguistic and linguistic-settlement mosaicism also allow us to assess the extent to which the linguistic and ethnic factor is taken into account in the formation of communities at the rayon level. It was most fully taken into account in the formation of communities in the former Vynohradiv, Rakhiv, Tiachiv and Uzhhorod rayons, where the indices decreased the most, especially the index of linguo-settlement mosaicism, which decreased by more than 60 percent (see *Table 1*).

The ethno-geographical factor also partially influenced the new rayon division. While the previous draft of the administrative-territorial division of the Zakarpattia Oblast did not provide for the allocation of a separate Berehove Rayon, such a rayon was formed in view of the position of Hungarian NGOs and Hungarian government agencies. It included all ethnically Hungarian settlements of the former Berehove and Vynohradiv rayons, but with several Ukrainian settlements. This was a compromise solution, as ethnic Hungarians raised the issue of creating a rayon based on all ethnic Hungarian settlements in the oblast, while some Ukrainian political circles opposed the creation of a rayon with its centre in Berehove. The ethno-geographic factor also influenced the configuration of the Tiachiv Rayon, which included several Romanian villages from the former Rakhiv Rayon, and the configuration of the Uzhhorod Rayon, which included the Hungarian village of Chomonyn from Mukachevo Rayon. It is important to note that the reconfiguration of the new rayons in Zakarpattia Oblast has only slightly changed the distances from ethnic minority villages to rayon centres.

Analysis of the conformity of the newly established administrative and territorial units and areas of settlement of ethnic minorities in Chernivtsi Oblast

Within Chernivtsi Oblast, there are areas of compact settlement of two related ethnic minorities – Romanians and Moldovans. In modern conditions, there is a self-awareness of their unity, but in the 2001 census, the Romanian and Moldovan languages and identities were recorded separately. According to the results of this census, ethnic Romanians constituted the majority in the former Hertsa Rayon (91.5%, with 92.2% speaking Romanian as their mother tongue), as well as a relatively significant share in the former Hlyboka (45.3% and 40.1%) and Storozhynets (36.8% and 35.4%) rayons, with Moldovans constituting the majority in the former Novoselytsia Rayon (57.5% and 54.7%) *(Table 2).* In Chernivtsi Oblast, there were 50 settlements with a majority Romanian-speaking population: there are 23 settlements in Hertsa Rayon, 16 in Hlyboka Rayon, 10 in Storozhynets Rayon, and one village in Novoselytsia Rayon.

Most of the population in 24 villages of the former Novoselytsia Rayon, one village of Hlyboka, Khotyn and Sokyriany rayons named Moldovan as their native language (see pop-stat.mashke.org 2024).

As a result of the administrative reform in Chernivtsi Oblast, instead of 11 rayons (Vyzhnytsia, Hertsa, Hlyboka, Zastavna, Kelmentsi, Kitsman, Novoselytsia, Putyla, Sokiriansk, Storozhynets, Khotyn), three new ones were formed (Vyzhnytsia, Chernivtsi, Dnistrovskyi). In fact, all densely populated Romanian and Moldovan villages, except for Mamalyha community, are part of Chernivtsi Rayon *(Figure 2)* that generally meets their interests in the light of preserving national and cultural identity. Considering the settlement of ethnic minorities, 12 territorial communities with a significant predominance of representatives of the Romanian and Moldovan minorities were also organised (Hertsa urban, Krasnoilsk rural, Boianivka, Vanchykivtsi, Voloka, Karapchiv, Ostrytsia, Petrivtsi, Sucheveny, Terebleche, Chudei rural communities in Chernivtsi Rayon, Mamalyha in Dnistrovskyi Rayon – see *Figure 2*). At the same time, due to the location of certain settlements, Novoselytsia urban, Kamianske, Mahala, Tarashany and Toporivtsi rural communities are ethnically mixed. The ethnic peculiarities of individual settlements in these communities were considered when creating starosta districts (part of a territorial community having its own officer delegated by a community council). The centres of territorial communities with a predominant or significant share of ethnic minorities are characterised by adequate accessibility to adjacent settlements and have the appropriate social and cultural infrastructure to meet the needs of the population.

In 2001, the index of ethnic mosaicism in Chernivtsi Oblast was higher than in Zakarpattia Oblast (0.414 vs. 0.342), while ethno-settlement mosaicism was slightly lower (0.323 vs. 0.336). The significant difference between ethnic and ethno-settlement mosaicism is explained by the difference between the share of ethnic minorities and the share of settlements where minorities predominate. As for linguistic and linguistic-settlement mosaicism, they were clearly higher in Chernivtsi Oblast (0.408 and 0.342, compared to the corresponding Zakarpattia indicators of 0.327 and 0.264).

The average values of linguistic and linguistic-settlement mosaicism of the former rayons of Chernivtsi Oblast (0.277 and 0.147), weighted by population, are significantly lower than the oblast indicators, which indicates that the linguistic and ethnic principle was considered to some extent when creating them. With the transition to territorial communities, the average linguistic mosaicism of the oblast decreased to 0.224 (by 19.0%), and the linguistic settlement mosaicism to 0.102 (by 30.6% – see *Table 2*). In other words, linguistic and ethnic principles are taken into account in the creation of communities, but to a lesser extent compared to Zakarpattia Oblast. The objective reason for this is that ethnic minorities are less densely populated in Bukovyna (see *Figure 2*).

*Table 2. Some indicators of the settlement of ethno-linguistic minorities in Chernivtsi Oblast by rayons before the 2020 administrative reform**

Administrative rayons and cities of regional significance (before 2020)	Share of population with Romanian mother tongue, %	Share of population with Moldovan mother tongue, %	Share of settlements with a Romanian-speaking majority in the total number of settlements, %	Share of settlements with a Moldovan-speaking majority in the total number of settlements, %	Index of linguistic mosaicism of former rayons	The index of linguo-settlement mosaicism of former rayons	Average index of linguistic mosaicism of territorial communities of former rayons	Average index of linguo-settlement mosaicism of territorial communities of former rayons	Percentage difference between the indices of linguistic mosaicism of former rayons and territorial communities	Percentage difference between the indices of linguo-settlement mosaicism of former rayons and territorial communities
Vyzhnytsia	0.3	0.1	0.0	0.0	0.029	0.000	0.029	0.000	-0.2	0.0
Hertsa	92.2	1.6	95.5	0.0	0.147	0.087	0.150	0.077	2.4	-11.2
Hlyboka	40.1	5.9	46.2	5.1	0.559	0.571	0.404	0.410	-27.8	-28.2
Zastavna	0.0	0.1	0.0	0.0	0.016	0.000	0.016	0.000	2.0	0.0
Kelmentsi	0.0	0.8	0.0	0.0	0.044	0.000	0.044	0.000	0.0	0.0
Kitsman	0.1	0.1	0.0	0.0	0.023	0.000	0.022	0.000	-3.1	0.0
Novoselytsia	9.3	54.7	4.9	63.4	0.576	0.495	0.496	0.428	-13.9	-13.4
Putyla	0.0	0.1	0.0	0.0	0.011	0.000	0.011	0.000	0.0	0.0
Sokyriany	0.0	3.0	0.0	3.4	0.177	0.131	0.172	0.111	-3.3	-15.3
Storozhynets	35.4	0.2	23.1	0.0	0.497	0.394	0.211	0.145	-57.6	-63.3
Khotyn	0.1	6.9	0.0	2.5	0.157	0.049	0.116	0.067	-26.0	38.0
Chernivtsi	3.3	1.1	0.0	0.0	0.348	0.000	0.348	0.000	0.0	0.0
Novodnistrovsk	0.1	0.5	0.0	0.0	0.248	0.000	0.248	0.000	0.0	0.0
Average for the oblast	*11.8*	*6.8*	*12.0*	*7.2*	*0.277*	*0.147*	*0.224*	*0.102*	*-19.0*	*-30.6*

*Calculated by the authors based on the data of the 2001 All-Ukrainian Population Census.

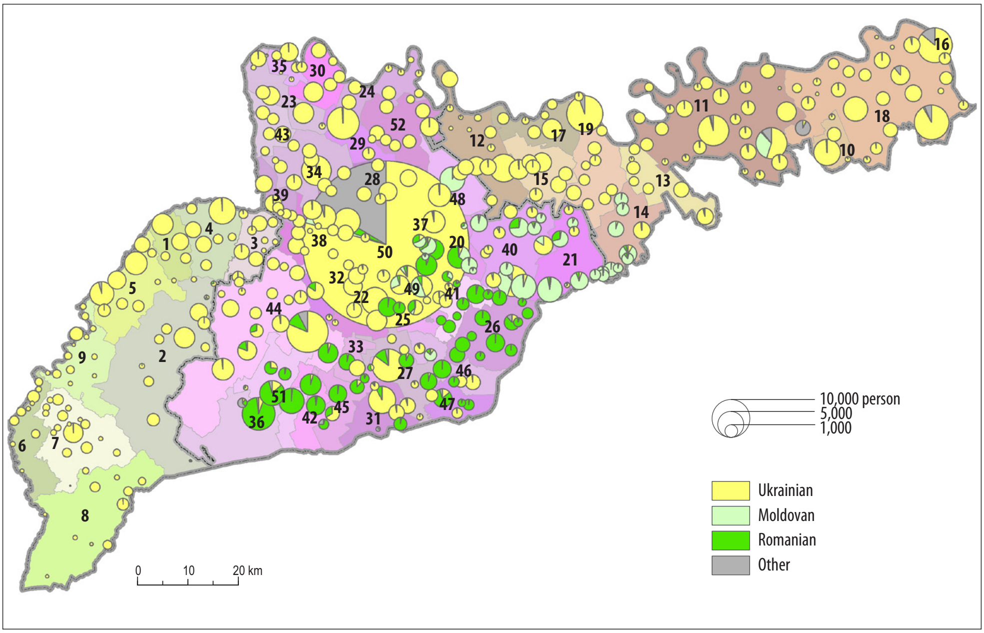

Fig. 2. The composition of the population of the settlements by native language in rayons and territorial communities of Chernivtsi Oblast formed as a result of the 2020 administrative reform. Territorial communities (1–52) of the newly created rayons: **I.** Vyzhnytsia Rayon: 1 = Banyliv; 2 = Berehomet; 3 = Brusnytsia; 4 = Vashkivtsi; 5 = Vyzhnytsia; 6 = Koniatyn; 7 = Putyla; 8 = Seliatyn; 9 = Ust-Putyla; **II.** Dnistrovskyi Rayon: 10 = Vashkivtsi; 11 = Kelmentsi; 12 = Klishkivtsi; 13 = Livyntsi; 14 = Mamalyha; 15 = Nedoboivtsi; 16 = Novodnistrovsk; 17 = Rukshyn; 18 = Sokyriany; 19 = Khotyn. **III**. Chernivtsi Rayon: 20 = Boiany; 21 = Vanchykivtsi; 22 = Velykyi Kuchuriv; 23 = Verenchanka; 24 = Vikno; 25 = Voloka; 26 = hertsa, 27 = Hlyboka, 28 = Horishni Sherivtsi; 29 = Zastavna; 30 = Kadubivtsi; 31 = Kamianec; 32 = Kamianske; 33 = Karapchiv; 34 = Kitsman; 35 = Kostryzhivka; 36 = Krasnoilsk; 37 = Mahala; 38 = Mamaivtsi; 39 = Nepolokivtsi; 40 = Novoselytsia; 41 = Ostrytsia, 42 = Petrivtsi; 43 = Stavchany; 44 = Storozhynets; 45 = Sucheveny, 46 = Tarashany; 47 = Terebleche; 48 = Toporivtsi; 49 = Chahor; 50 = Chernivtsi; 51 = Chudei; 52 = Yurkivtsi. Based on the results of the 2001 All-Ukrainian Population Census. *Source*: pop-stat.mashke.org/ukraine-census-2001-lang/cernivecka.htm 2024

The average values of the indices of language and language-settlement mosaicism in the transition to municipalities decreased the most in the former rayons of Storozhynets and Hlyboka with a mixed ethno-linguistic composition of the population (the share of Romanian-speaking population in 2001 was 35.4 and 40.1%, respectively). In the case of the old Novoselytsia Rayon, where the mosaicism of the population was also high (54.7% mentioned Moldovan as their mother tongue, 9.3% Romanian), the language and settlement mosaicism decreased by only 13–14 percent as a result of the reform.

Analysis of the conformity of the newly established administrative and territorial units and areas of settlement of ethnic minorities in Odesa Oblast

The most ethnically mosaic in Ukraine is the south-western part of Odesa Oblast, i.e. the historical region of Budzhak (ethnic mosaic index in 2001 was 0.735, ethnic settlement index was 0.653, linguistic index was 0.728, linguistic settlement index was 0.673) with areas of compact settlement of the following ethnic minorities: Bulgarians, Moldovans, Russians (sub-ethnic group of Old Believers), and Gagauzes. The former rayons of the region were also characterised by a high degree of linguistic and ethnic mosaicism: according to the 2001 data, the indicators of language and language-settlement mosaicism did not reach the value of 0.5 only in Bilhorod-Dnistrovskyi and Tatarbunary rayons *(Table 3)*.

The largest area is inhabited by the Bulgarian ethnic group *(Figure 3)*, which, according to the 2001 census, constituted an absolute majority in the former Bolhrad Rayon (60.8% of ethnic Bulgarians, 57.5% of the population with Bulgarian as their mother tongue), a relative majority in Artsyz (39.0 and 34.0%, respectively), and Tarutyne (37.5 and 31.7%). There are 49 settlements in the south-western part of Odesa Oblast with a Bulgarian-speaking population majority: 19 villages in the former Tarutyne Rayon, 13 settlements in Bolhrad Rayon, 7 villages in Artsyz Rayon, 6 settlements in Izmail Rayon, 2 villages in Sarata Rayon and 2 in Tatarbunary Rayon (see pop-stat.mashke.org 2024).

The autochthonous ethnic Russian population (a sub-ethnic group of Old Believers) lived mostly along the Danube and in the central part of Budzhak (see *Figure 3*). In 2001, the Russian-speaking majority was recorded in 44 settlements, including the cities of Izmail and Bilhorod-Dnistrovskyi, 11 settlements of the former Tarutyne, 9 settlements of Artsyz, 6 of Kiliia, 5 of Sarata, 5 villages of Izmail, 3 of Bolhrad, 2 of Bilhorod-Dnistrovskyi, and 1 of Tatarbunary rayons.

The settlement of ethnic Moldovans in Odesa Oblast is formed both by a compact area in the south-western part of Budzhak region and by separate settlements in its northern (Podil) part. The largest number of villages (26) with a predominance of Moldovan-speaking population were in Budzhak part of Odesa Oblast, in the former Reni (5 villages), Sarata (5), Tarutyne (5), Izmail (4), Kiliia (4), Tatarbunary (2) and Bilhorod-Dnistrovskyi (1) rayons *(Figure 3)*. In the northern part of the oblast, ethnic Moldovans constituted the majority in 5 villages of Podil Rayon (Hyderym, Kazbeky, Oleksandrivka, Lypetske, Stara Kulna), Tochylove village of Ananiv Rayon and Rozivka village of Okny Rayon.

Only in 5 villages of Odesa Oblast the majority of the population were Gagauzes: Dmytrivka, Oleksandrivka, Vinohradivka (former Bolhrad Rayon), Kotlovyna (former Reni Rayon), Stari Troyany (former Kiliia Rayon) (see pop-stat.mashke.org 2024).

Despite the significant mosaic of ethnic minority settlements in the south-western (Budzhak) part of Odesa Oblast, their wishes in this region were partially taken into account during the administrative reform. This concerns, first, the rayon division, as according to the proposals of Bulgarian NGOs, Bolhrad Rayon was created, which included settlements with a majority of ethnic Bulgarians in three former rayons – Artsyz, Bolhrad, Tarutyne. The majority of territorial communities in this rayon are also dominated by ethnic Bulgarians (see *Figure 3*).

The areas of residence of other autochthonous ethnic minorities (Gagauz, Moldovans, Russian Old Believers) had an area and population that did not meet the criteria of a rayon, so only in some cases in the newly created Izmail Rayon were territorial communities with a predominance of one ethnic minority organised on their basis. Thus, outside Bolhrad Rayon, only two communities can be called predominantly ethnically homogeneous: Reni urban community with a predominance of ethnic Moldovans and Vylkove urban community with a predominance of Russian Old Believers. Since the Gagauz villages are not compactly located, there were no prerequisites for the creation of territorial communities with a predominance of Gagauz people in the region. Therefore, given the close proximity of settlements of different ethnic composition, a number of territorial communities in areas where ethnic minorities are settled could not but have an ethnically mixed character.

Difficulties in taking into account the ethnolinguistic principle in the formation of territorial communities in Budzhak are also reflected in changes in the mosaic indicators: weighted average language and language-settlement mosaicism in the transition from

*Table 3. Some indicators of the settlement of ethno-linguistic minorities of Budzhak part of Odesa Oblast by rayons before the 2020 administrative reform**

Administrative rayons and cities of regional significance (before 2020)	Share of the population with Russian as their mother tongue, %	Share of the population with Bulgarian as their mother tongue, %	Share of population with Moldovan ad their mother tongue, %	Share of the population with Gagauz as their mother tongue, %	Share of settlements with a Russian-speaking majority in the total number of settlements, %	Share of settlements with a Bulgarian-speaking majority in the total number of settlements, %	Share of settlements with a Moldovan-speaking majority in the total number of settlements, %	Share of settlements with a Gagauz-speaking majority in the total number of settlements, %	Index of linguistic mosaicism of former rayons	The index of linguo-settlement mosaicism of former rayons	Average index of linguistic mosaicism of territorial communities of former rayons	Average index of linguo-settlement mosaicism of territorial communities of former rayons	Percentage difference between the indices of linguistic mosaicism of former rayons and territorial communities	Percentage difference between the indices of linguo-settlement mosaicism of former rayons and territorial communities
Artsyz	42.8	34.0	3.1	0.8	46.2	30.8	0.0	0.0	0.667	0.639	0.622	0.532	-6.8	-16.8
Bilhorod-Dnistrovskyi	13.0	0.5	5.0	0.2	3.5	0.0	1.8	0.0	0.328	0.101	0.432	0.065	31.4	-35.6
Bolhrad	16.3	57.5	1.0	17.8	9.1	59.1	0.0	13.6	0.608	0.603	0.535	0.436	-11.9	-27.8
Izmail	21.6	24.9	26.2	0.3	26.1	34.8	17.4	0.0	0.754	0.733	0.531	0.544	-29.6	-25.8
Kiliia	44.2	2.5	12.8	3.7	36.8	5.3	21.1	5.3	0.656	0.715	0.599	0.582	-8.6	-18.6
Reni	37.9	6.6	40.8	6.8	0.0	12.5	62.5	12.5	0.676	0.563	0.676	0.563	0.0	0.0
Sarata	21.4	19.1	17.6	0.1	15.4	7.7	15.4	0.0	0.716	0.568	0.553	0.429	-22.8	-24.5
Tarutyne	32.9	31.7	12.7	3.3	28.0	38.0	16.0	0.0	0.739	0.719	0.715	0.673	-3.2	-6.4
Tatarbunary	7.7	10.7	8.5	0.1	2.8	5.6	5.6	0.0	0.451	0.252	0.418	0.410	-7.4	62.8
Bilhorod-Dnistrovskyi	54.3	1.6	1.2	0.2	66.7	0.0	0.0	0.0	0.529	0.444	–	–	–	–
Izmail	74.2	4.6	1.8	0.4	100.0	0.0	0.0	0.0	0.414	0.000	–	–	–	–
Average for the region	*35.2*	*17.9*	*10.3*	*3.4*	*18.7*	*19.4*	*10.6*	*1.8*	*0.581*	*0.461*	*0.543*	*0.434*	*-6.5*	*-5.9*

*Calculated by the authors based on the data of the 2001 All-Ukrainian Population Census.

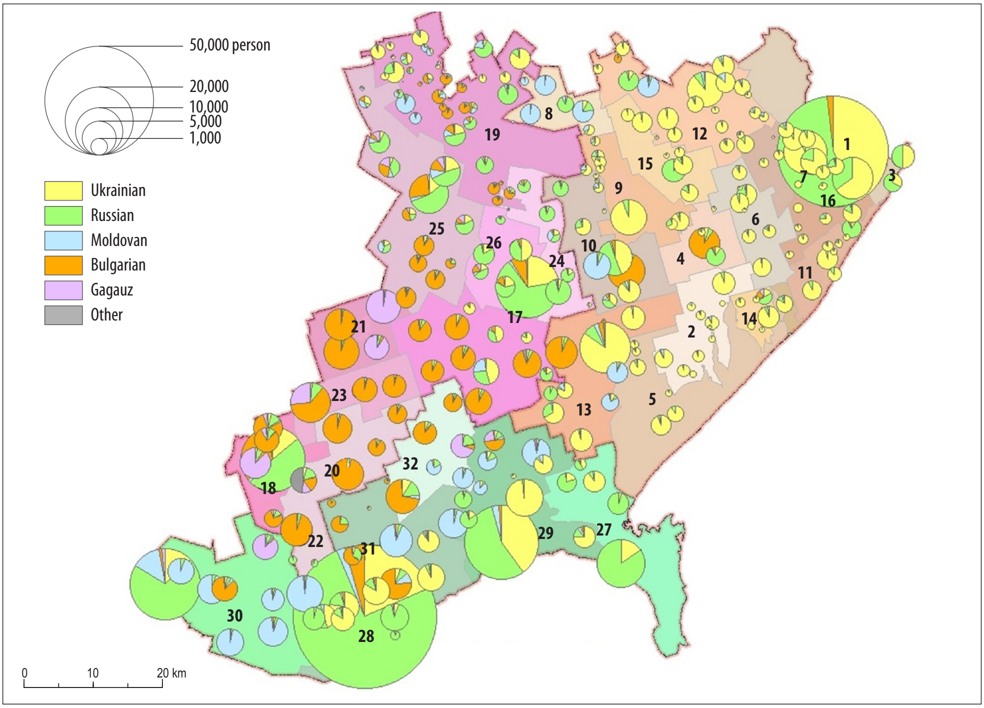

Fig. 3. The composition of the population of the settlements of rayons and territorial communities by native language in the southern part of Odesa Oblast formed as a result of the 2020 administrative reform. Territorial communities (1–32) of the newly created rayons: **I.** Bilhorod-Dnistrovskyi Rayon: 1 = Bilhorod-Dnistrovskyi; 2 = Dyviziya; 3 = Karolino-Buhaz; 4 = Kulevcha; 5 = Lyman; 6 = Marazliivka; 7 = Moloha; 8 = Petropavlivske; 9 = Plakhtiivka; 10 = Sarata; 11 = Serhiivka; 12 = Starokozache; 13 = Tatarbunary; 14 = Tuzly; 15 = Uspenivka; 16 = Shabo. **II.** Bolhrad Rayon: 17 = Artsyz; 18 = Bolhrad; 19 = Borodino; 20 = Vasylivka; 21 = Horodnie; 22 = Krynychne; 23 = Kubei; 24 = Pavlivka; 25 = Tarutyne; 26 = Teplytsia. **III**. Izmail Rayon: 27 = Vylkove; 28 = Izmail; 29 = Kiliia; 30 = Reni; 31 = Safiany; 32 = Suvorove. Based on the results of the 2001 All-Ukrainian Population Census. *Source*: pop-stat.mashke.org/ukraine-census-2001-lang/odeska.htm, 2024.

previous rayons to communities decreased by only 6 percent (see *Table 3*). A significant decrease in linguistic mosaicism was recorded only during the reorganisation of Izmail and Sarata rayons. It is interesting to note the significant increase in the average indicator of linguo-settlement mosaicism in Tatarbunary Rayon. This is due to the significant influence on the weighted average of the most populated Tatarbunary territorial community, which included all settlements of the former rayon with a predominance of ethnic minorities, and therefore has a high index of linguo-settlement mosaicism (0.584).

Given the significant powers granted to territorial communities in the process of administrative-territorial reform, it can be concluded that the creation of such administrative units with a predominance of ethnic minority populations provides the prerequisites for the organisation of their self-government, including the election of leaders, budget allocation and the formation of a programme of socio-economic development. But the true impact of the administrative-territorial reform on the livelihoods of ethnic minorities will be revealed over time, primarily depending on the capacity of communities to fill the provided framework with content.

Conclusions

In the process of administrative-territorial reform in Ukraine, given the voluntary nature of the first stage of merging settlements, ethnic minority populations compactly located in Zakarpattia, Chernivtsi and Odesa oblasts were given the opportunity to organise majority-ethnic communities and elect governing bodies, which in most cases was successfully implemented. If certain settlements were remote from the main compact settlement area of the respective ethnic minority, they were in most cases entitled to create their own separate starosta district.

As the Ukrainian experience shows ensuring greater correspondence between the units of the administrative-territorial structure and areas of compact settlement of ethnic minorities is necessary and feasible only for compactly located settlements with a predominance of ethnic minority population and taking into account the criteria and procedure for the formation of administrative units. At the same time, the self-government of dispersed ethnic minorities formed in the process of migration can only be realised in an extra-territorial form.

The distinctive settlement patterns of ethnic minorities and the wishes of their community organisations were only partially taken into account in the formation of new rayons and the selection of rayon centres, which in most cases was limited by the defined criteria for the size of new administrative units and political reasons.

Administrative-territorial reforms can be an effective tool to meet the cultural and economic needs of ethnic minorities and to expand their rights if they are aimed at reducing the ethnic mosaicism of the newly formed units and giving them greater powers in the process of decentralisation.

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A critical review of dark tourism studies

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Abstract

The topic of dark tourism emerged in the last three decades as tourism became more accessible. It allows forgotten history to be revised and transferred to the public. This study aims to restructure existing categorization regarding dark tourism and address the research gaps in dark tourism studies. We collected studies from international publication databases – Scopus, Web of Science, and Google Scholar. We pre-processed the following data for each study: topic, authors' location of university affiliation, study area, year of publication, top-cited articles, top productive journals in publishing dark tourism studies, keywords, and internality/externality of the author from the study area. With the current paper, we analysed review articles published from 1996 to 2024 (first quarter), applying qualitative methods. Based on these, a new analytical framework was generated. Furthermore, the connections between research topics were also analysed. The results of the analysis highlight specific research gaps in the literature on dark tourism and address poorly visible research fields in international journals, e.g. terrorism-related research, social media links of dark tourism, postcolonial contexts, or commemoration of communist past and heritage. Consequently, certain countries and regions are underrepresented in the literature. This critical review offers new research areas but also gives some directions to the theoretical enrichment of the dark tourism concept.

Keywords: thanatourism, commemoration, categorization, connections, 4E concept

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Introduction

The tourism and hospitality industry was exponentially growing and progressing in innovations before the worldwide lockdowns due to the COVID-19 pandemic. Over time, increasing numbers of destinations have been opening up and investing in tourism growth, making modern tourism one of the core drivers of socio-economic change. Due to the strengthening competition, innovation became a crucial element of tourism development (Streimikiene, D. *et al*. 2020). Despite the increasing study on dark tourism, there is still much to learn about its potential to boost the travel and tourism sector after COVID-19. Most of the researches ignored dark tourism's inventive and economic contributions to the industry's comeback in favour of concentrating on its psychological and social elements.

Technological change, governmental attitudes and aims, changing regulations (e.g. permeability of borders), and evolving customer motivations influence the direction of tourism development. Thus, various directions have emerged recently in innovative global tourism. Innovation includes new things not done before and a recreation of existing tourism products to be more competitive. There are different processes forc-

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ing innovation in the tourism industry. In our paper, innovation is understood as occurring in three directions. First, innovative mass tourism uses smart tourism tools such as digitalization, artificial intelligence, 5G, and service-oriented robotics. Second, technological change has contributed to the emergence of a sharing economy in tourism. For instance, Airbnb (Cheng, M. and Foley, C. 2019; Bresciani, S. *et al.* 2021) and other peer-to-peer platforms pose new and robust competition for traditional accommodations (e.g. hotels). Third, niche tourism prompts innovation. On the one hand, governments consider economic aspects; on the other, they often focus on social, cultural, or even spiritual aspects of tourism. Changing regulations have made travel more accessible (i.e. easier, faster, and cheaper), contributing to the growing number of domestic and international tourists (Proos, E. and Hattingh, J. 2022). More and more customers seek individualized and personalized experiences that differ from mass tourism. Thus, there is a growing demand for niche tourism (Bunghez, C.L. 2021).

The significance of the dark tourism concept can be explained with the help of the 4E model which combines four fields: emotions, experiences, education, and entertainment (Assylkhanova, A. 2022). This model underscores the multifaceted nature of dark tourism, balancing theoretical concepts with practical tourism products (Isaac, R.K. 2022). Moreover, other factors such as the growing popularity of the co-creation of knowledge and recognition of the importance of commemoration are also significant aspects to be considered when planning and implementing tourist activities. Dark tourism aims to use underutilized potential attractions such as battlefields, cemeteries, disaster sites, concentration camps, memorials, volcano creeks, and killing fields to provide answers to the challenges concerning the abovementioned factors.

This paper presents a critical review of dark tourism literature, which began gaining research interest around 30 years ago and is generating increasing curiosity among researchers. This paper's primary aim was to analyse the scientific literature on dark tourism. Thus, this work identifies the state of current dark tourism literature, trends in the topics, and areas for future research and dark tourism sites. The study aims to co-create knowledge about dark tourism activity and support cooperative education between dark tourism sites and academic researchers. Previous studies have examined several aspects of dark tourism, such as its causes and effects (Sharpley, R. and Stone, P.R. 2009; Biran, A. *et al.* 2011; Causevic, S. and Lynch, P. 2011). However, there is a knowledge deficit about its implementation and ramifications in emerging markets because these studies mainly concentrate on Western contexts. This study fills this gap by looking at dark tourism from a broader, international viewpoint, enhancing current research. Recent studies (Cai, *et al.* 2022; Radzevičius, M. 2022) have begun to explore the intersection of dark tourism and post-pandemic recovery, indicating a burgeoning interest that this paper seeks to develop further.

This study addresses the following gaps:

- Comprehensive literature review: Mapping the current landscape of dark tourism research to identify prevailing trends and gaps.
- Post-pandemic recovery: Exploring the role of dark tourism in the recovery and innovation of the tourism industry following the COVID-19 pandemic.
- Sustainable integration: Proposing frameworks for integrating dark tourism into sustainable tourism practices to enhance economic resilience and cultural preservation.

The practical significance of this research is twofold. Firstly, dark tourism offers a means to transform mindsets and commemorate crucial moments in human history, thereby enriching collective memory and cultural heritage. Secondly, in the wake of the COVID-19-induced crisis and recession within the tourism sector, dark tourism presents a viable source for economic revitalization and innovation, contributing to the broader recovery efforts of the industry.

A review of dark tourism studies

Dark tourism is not a new phenomenon; research began in the 1990s, and its popularity has increased, despite most of the relevant articles were published after 2010. The rapidly expanding body of research should be surveyed systematically to provide an overview of the state of the art in the field, supporting future studies. We comprehensively reviewed existing English-language peer-reviewed articles on dark tourism from Scopus, Web of Science, and Google Scholar, collecting the data on the year of publication, location of university affiliation of the authors, research area, study topics and categories, and keywords used. We compiled these into a database we could use for the data analysis.

Literature review

Articles regarding dark tourism began appearing in well-cited peer-reviewed journals in 1996. However, the number of studies on the discussed topic has sharply increased in the last decade. The overall trends in fresh articles have been more about defining the scope of dark tourism; identifying visitors' experiences and emotions at dark tourism sites; and political dimensions regarding the relationship with collective memory (Buckley, R. 2012; Light, D. 2017). Light identified key issues and themes in dark tourism and assigned priority levels to the individual topics: one star for the lowest research priority and three for the highest priority (Light, D. 2017).

Dark tourism research works have concentrated on the following directions of the currently discussed area: the concept of dark tourism itself (Cole, T. 1999; Lennon, J.J. and Foley, M. 1999; Lennon, J.J. and Malcolm, F. 2002; Lennon, J.J. and Seaton, A.V. 2004; Bowman, M. and Pezzullo, P. 2009; Sharpley, R. 2009; Sharpley, R. and Stone, P.R. 2009); ethical issues related to the living and the dead (Cole, T. 1999; Lennon, J.J. and Foley, M. 1999; Stone, P.R. 2006; Sharpley, R. 2009; Sion, B. 2014); the politics of the dark tourism industry (Sharpley, R. 2009; Causevic, S. and Lynch, P. 2011; Carrigan, A. 2015); the main motives of visitors (Best, M. 2007; Biran, A. *et al.* 2011; Hyde, K. and Harman, S. 2011; Biran, A. and Hyde, K.F. 2013). From the literature, there is no globally accepted definition of dark tourism or what it encompasses. All authors have operated from their understandings of and explanations for it.

Spanning educational purposes to thrill-seeking and commemorative motives, dark tourism research has examined a variety of tourist motivations and experiences (Biran, A. *et al.* 2011; Dunkley, R.A. *et al.* 2011). At dark tourism sites, visitors frequently experience emotional reactions like sadness, curiosity, and excitement. Their actions often reveal a complicated interplay between sensationalism and sincere commemoration (Wight, C.A. and Lennon, J.J. 2007; Stone, P.R. and Sharpley, R. 2008). The management of dark tourism destinations presents particular difficulties on the supply side, such as ethical issues regarding the depiction of tragedy and the participation of tourists in delicate historical contexts (Ashworth, G.J. 2004; Hartmann, R. 2014).

Several general patterns and directions emerge from the studies we analysed. For example, researchers from former colonizing countries use ample accessible data to conduct comprehensive investigations of dark tourism sites within their previous colonies (Burroughs, J. 2015; Sharma, N. and Rickly, J.M. 2018; Jamalian, M. *et al.* 2020). Another trend is the regretful and commemorative writing in Jewish, Polish, and German researchers' works about the Holocaust (Biran, A. *et al.* 2011; Cohen, E.H. 2011; Bakota, D. *et al.* 2020; Sawczuk, M. 2020), or Ukrainian authors' writings on the Chernobyl nuclear accident (Zerva, K. 2017; Bakota, D. *et al.* 2020). What is evident from these observations is that the primary research sites are in the past colonies of developed countries, in underdeveloped and developing countries, and in places that have experienced war or other disputes. In the study of dark and discordant heritage, Ashworth's work has been essential, especially when analysing how societies commemorate difficult pasts like slavery (Ashworth, G.J. 2004). In his discussion of the function of heritage tourism in presenting contested histories, Ashworth draws attention to the "dissonance" that might occur when various groups have divergent interpretations of historical events (Ashworth, G.J. and Tunbridge, J.E. 1996). His observations offer a starting point for comprehending the difficulties and moral dilemmas of overseeing dark tourism destinations. It is important to highlight these evident logical research tendencies to create groupings related to the study areas of the articles on dark tourism.

Although research on dark tourism has focused on a variety of historical and cultural settings, slavery history has received a lot of attention as a critical component of dark tourism in Africa, particularly in Ghana. The cultural and ethical challenges of portraying this traumatic past have been demonstrated by researchers such as Yankholmes, A.K.B. and McKercher, B. (2015), who have investigated visitors' experiences and perceptions of slavery heritage sites like Ghana's Cape Coast and Elmina Castles (Yankholmes, A.K.B. 2009; Mowatt, R.A. and Chancellor, S.H. 2011). Notwithstanding these efforts, there is still a demand for more research in this field since it does not thoroughly examine other African countries or relate the broader ramifications of slavery tourism to dark tourism practices elsewhere.

Researchers have used both inductive and deductive approaches to studies of dark tourism. Some authors apply a specific theory to the dark tourism industry (Ivanova, M. and Buda, D.M. 2020); others perform standard empirical research, reviewing the literature to develop hypotheses, conducting the study, collecting and analysing the data, and drawing generalizations from the results (Hartmann, R. 2014; Light, D. 2017; Pliakas, T. 2017; Mionel, V. 2020; Lim, S. and Kim, J. 2023; Mora Forero, J.A. *et al.* 2023). Ivanova, M. and Buda, D.M. (2020) apply Deleuze and Guattari's concept of "rhizomatic thinking" to dark tourism in the context of communist heritage; their analysis enables openness through a dynamic, heterogeneous, non-linear, decentralized approach. Rhizomes are networks cutting across boundaries of hierarchies, categories and move beyond dualistic understandings of concepts or legacies. Via rhizomatic thinking, the authors connect experiences and memories of communism with the present interpretations of communist heritage, exploring the topic as a process of shifting connectivity rather than a confined and permanent construct. Moreover, the importance of historical and cultural memory in the growth of post-communist tourism is highlighted by studies on dark tourism in Romania and Bulgaria. Schneider, A. *et al.* (2021) highlight the possibility of targeted tourism policies by identifying the variables that motivate tourists to visit Romania's dark sites, including the Sighet prison. Mileva, S. (2018) examines Bulgaria's undeveloped dark tourism industry, emphasizing the necessity of a culturally sensitive strategy that considers the country's distinct historical background. Patrichi, I.C. (2013) provides other examples of the allure of dark tourism destinations, such as Romania's Merry Cemetery, by shedding light on their reflecting and emotional appeal. When taken as a whole, these studies highlight how the niche might influence post-communist identity and economic development.

Furthermore, there have been significant deductive contributions to the notion of dark tourism. In one, Light, D. (2017) introduces the term *thanatourism* to describe dark tourism and tracks the evolution of academic research on the topic over the 1996–2016 period. He also provides a kind of categorization of sites that are analysed in dark and thanatourism research. Similarly, Light, Pliakas provides a comprehensive content analysis, focusing on definitions of dark tourism, theories, and dark tourism spots around the globe (Pliakas, T. 2017). Hartmann, R. (2014) presents new directions in contemporary tourism research by investigating previously studied dark tourism concepts, in reviewing the history of the field, Hartmann highlights the focus on sites with shadowed history. Focusing on development possibilities, a group of Colombian researchers has prepared an analytical review of the tendencies of dark tourism as a new industry direction in Cundinamarca, Colombia (Moisés, J. *et al.* 2020).

Starting from the results of the previous analyses aims to extend the knowledge of dark tourism by updating the time frame and offering a broader multidimensional perspective that includes emerging non-Western markets that are often underrepresented in earlier analyses. Unlike Light, D. (2017), and Moisés, J. *et al.* (2020) which focused primarily on thematic and conceptual categories, this study integrates regional variations and explores the role of black tourism recovery after the COVID-19 pandemic. By examining the intersections between sustainable tourism practices and economic resilience, this study provides a new framework for understanding the evolving impact of dark tourism worldwide.

The methods for analysing the spheres of tourism are diverse, although qualitative methods are used most often (Wight, C.A. 2006; Biran, A. and Hyde, K.F. 2013; Friedrich, M. and Johnston, T. 2013). Commonly, the studies are conducted as observations of tourists' behaviours and in-depth interviews; extensive surveys are not particularly popular in dark tourism papers (Wight, C.A. 2006; Biran, A. and Hyde, K.F. 2013). One additional qualitative method in dark tourism research is criticism of secondary textual materials (Lennon, J.J. and Foley, M. 1999) such as books, travel blogs, movies (Zerva, K. 2017; Bakota, D. *et al.* 2020), and website content including social media posts (Bertoldi, D. *et al.* 2020; Kerr, M.M. *et al.* 2020; Wyatt, B. *et al.* 2021). Compared to the previously published review articles, our research has a different focus on analysing regional differences. Moreover, by using Light's (2017) research as a starting point, we aim to logically categorize topics. In addition, we explore the connection between various dark tourism-related topics.

Data and methods

With this study, our aim was to categorize and sort the currently available literature regarding dark tourism and highlight the gaps in the research. The sources of the articles obtained for this study were Scopus, Web of Science, and Google Scholar. For this research, we considered both touristic and non-tourism and hospitality journals. We collected peer-reviewed articles written in English and research in various other languages with translated abstracts to English from 1996 to 2024 (first quarter). We collected the sample data over a reasonably limited period because the main aim was to show the patterns and trends in the research on dark tourism rather than discuss details of each empirical study and identify gaps in the literature.

Regarding data availability, Google Scholar is open to everyone, whereas the other two were available through our institution's subscriptions. We identified a final number of 519 papers on dark tourism, which served as the only search term; adding more search terms would have inevitably yielded more results, but we wanted to focus solely on the results on dark tourism. For each paper, in a database created with the following fields: the title, location of affiliation of authors, the study area of the paper, year of publication, top-cited articles, top productive journals in dark tourism studies, keywords, whether the author was internal or external to the site being studied, and the abstract.

As stated in *A review of dark tourism studies* section, previous researchers have used qualitative methods such as observations of tourists' behaviours and in-depth interviews and quantitative methods such as clustering subtopics. We analysed review articles published from 1996 to 2024 applying qualitative methods. First, we sorted the collected review data for input into an Excel tool called Pivot Table to produce graphs, maps, and tables for analysis; we also compiled a categorization table that emerged from the document analysis. Each heading is derived from a combination of the NVivo word cloud of the keywords in the works reviewed.

Results

Here we present and discuss the study findings according to our three main groupings.

For descriptive analysis we have statistically processed the data; analysing the year of publication and the university affiliation of the authors, the study area, and the geographical relation of the authors to the study area. Last but not least, we also analyse the connection between the keywords and research topics.

Year of publication and authors' location of university affiliation

In 30 years, 519 published peer-reviewed articles related to dark tourism were included in Scopus, Web of Science, and Google Scholar. In the first decade, there were fewer than ten studies because dark tourism as an industry sector was not yet recognized at all. Between 2001 and 2010, there were slightly more scientific papers about dark tourism (36), but the highest interest in dark tourism and its constituents has been observed in the last decade. Rapid growth in the amount of work is connected to different reasons that will be discussed later in this paper.

One of the crucial factors in the analysis is the settings of the dark tourism studies and the authors' university locations; this elucidates the global interest in dark tourism research. *Figure 1* presents the top 10 authors' university locations of dark tourist studies. We counted 71 authors' university locations among the 519 papers.

Two main groups of countries emerge from the analysis: the first one is where most of the research funds, opportunities, and infrastructures are concentrated, while the countries in the second experienced events that can be the basis of dark tourism activities. *Figure 1* presents countries that have been researching the topic of dark tourism for the last thirty years. Five countries are in Europe, and the United States, and Australia. The European nations are the developed countries, the remainings are countries that have suffered various forms of brutality, mass mortality, or other violent events in their history. There were also a small number of articles by multiple authors collaborating from varying countries. *Figure 2* presents a Leopold matrix of articles released yearly from 1996 to 2024 in the top ten author source countries.

Publications on dark tourism increased in number over time. The UK, the United States, and Australia were the first countries where dark tourism was considered independently before 2011. It can be stated that 2011 marks the take-off point of the global scientific interest in dark tourism itself.

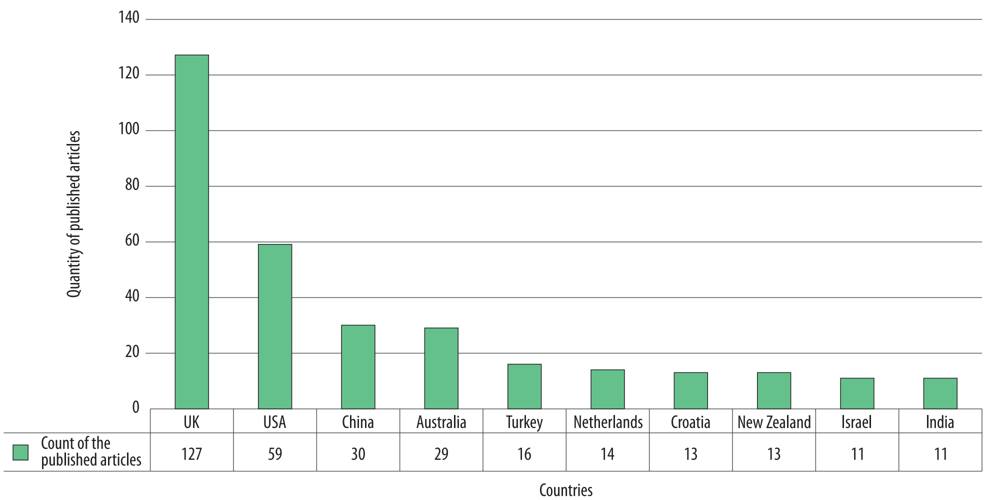
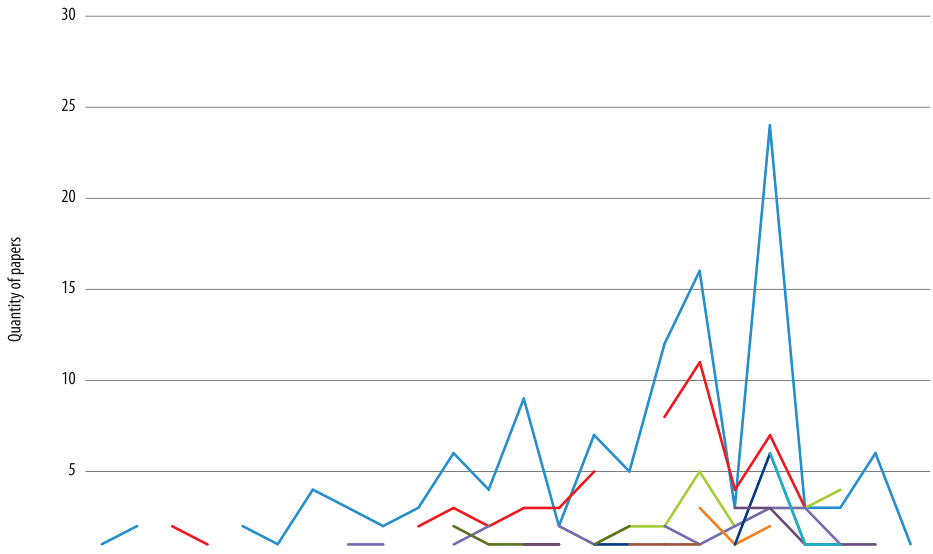


Fig. 1. Top 10 authors' university locations of dark tourism-related articles. *Source:* Elaborated by the authors



	1990	1999	2002	2003	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
UK	1	2			2	1	4	3	2	3	6	4	9	2	7	5	12	16	3	24	3	3	6	1
USA			2	1						2	3	2	3	3	5		8	11	4	7	3		1	
China											1			2	1	2	2	5	2	3	3	4		2
Australia				1		1		1	1		1	2		2	1		2	1	2	3	3	1		
Turkey								1				1		1		2		3		6	1	1		
Netherlands													1	1		1		3	1	2			1	
Croatia											1		1		1	1			1	6	1			
New Zealand						1							1	1		1	1	1		2			1	
Israel											2	1	1		1	2			1		2			
India													1	1					3	3	1	1	1	

Fig. 2. Number of articles by year of publication and the origin of authors by countries (top 10).
Source: Elaborated by the authors.

Targeted study areas and their internal/external relation to the university affiliation of authors

In addition to knowing the location of the university affiliation of authors of dark tourism-related articles, it was essential to see the investigation target countries. *Figure 3* presents a world map highlighted to reflect regions analysed in the last three decades; the colours reflect the intensity of research output based on the number of published articles (darker colour means more articles). The United Kingdom, the United States, and China produced darkest tourism papers, from 16 to 40 on a particular study area. There was a moderate number of papers on sites in Australia, Indonesia, Japan, the Central European states, and Turkey, and there were few sites investigated in Canada, African countries, Central Asia, and some Western European states. The map visually highlights the research gaps in grey as undetected dark tourism sites. We note that the authors of 135 articles examined the dark tourism industry worldwide rather than in particular locations. Most of these articles are theoretical or conceptual papers, that mention specific locations as examples but have not conducted any particular empirical research.

Figure 4 presents the number of works produced based on whether the author was internal or external to the study area. It was considered an indicator of unevenness (e.g. centre-periphery relations) in producing scientific output within dark tourism as a research topic. We consider an author internal if their institutional affiliation was in the same country

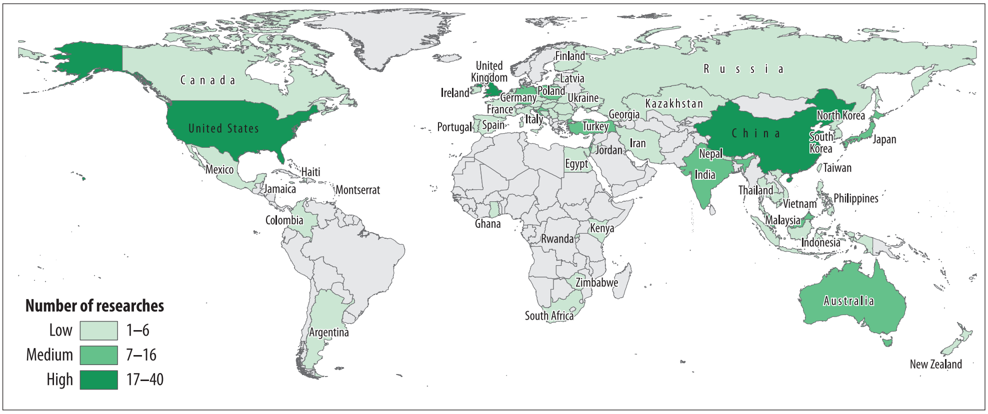


Fig. 3. World map of the dark tourism study areas in this review. *Source:* Elaborated by the authors.

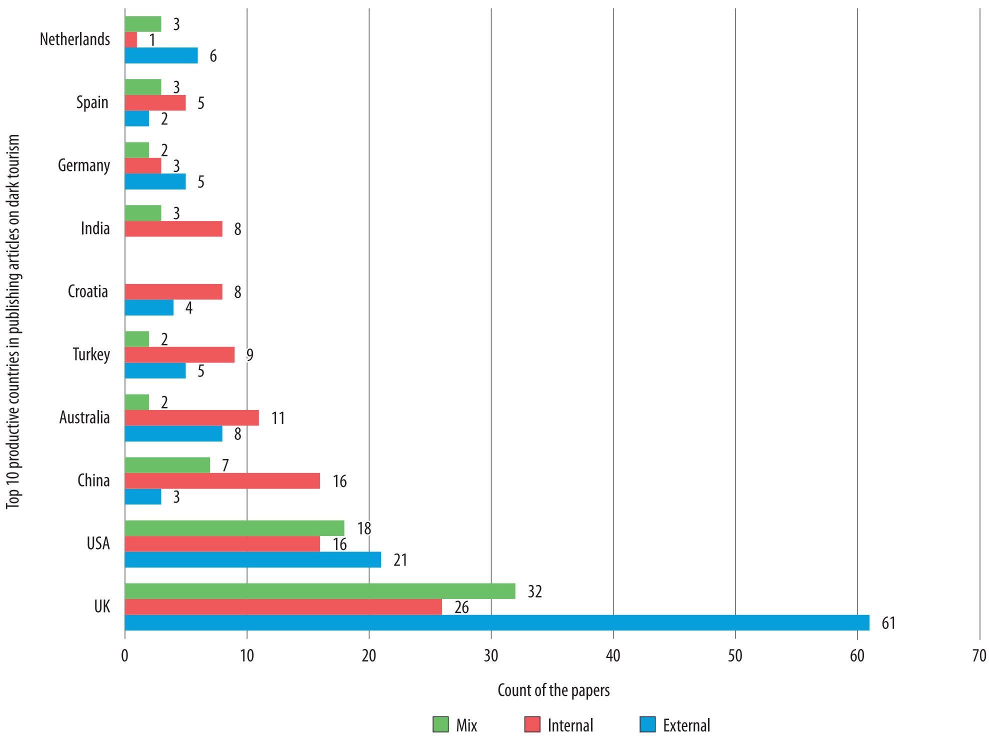


Fig. 4. Internality and externality of the authors to the analysed region (top 10). *Source:* Elaborated by the authors.

where their study located and external if it was outside the country. Only the affiliations were considered; i.e. the authors' nationalities were not analysed since these data are often unavailable. Only the first authors were analysed – but according to our survey, in most cases, the lists of authors were entirely internal (59.3%) or external (34.9%). The figure shows that the UK is the leader in publishing articles on dark tourism themes in all aspects: external, internal, and mixed study areas (a combination of internal and external). Overall, authors from the UK, the United States, Australia, and Germany studied areas outside their own countries; in the remainder of the top 10 countries, authors studied dark tourism within their own countries. We suggest that the first four states, being developed Western nations, simply have more resources and possibilities to conduct and publish research worldwide.

Most cited articles and their brief content

To understand the overall trends, topics, and comprehension of the highly cited articles, we have compiled *Table 1* of the top 10 most cited articles in dark tourism research (as per Web of Science, Google Scholar, and Scopus). The leader in this list is Philip R. Stone with his article "A dark tourism spectrum: Towards a typology of death and macabre related tourist sites, attractions, and exhibitions" published in 2006 in *Tourism*. This article discusses the concept of dark tourism and proposes a typology to categorize various dark tourism sites based on their intensity and characteristics. Stone introduces the idea of a "spectrum" to illustrate the varying degrees of darkness associated with different tourist sites and attractions related to death and the macabre.

The second cited article in the list is "Dark tourism" by John J. Lennon. He reviews two decades of research on dark tourism and thanatourism, highlighting key themes and debates (Lennon, J.J. 2017a). The article evaluates the definitions, ethical issues, political dimensions, demand, management, and research methods related to dark tourism, and argues that dark tourism often overlaps with heritage tourism. Whereas, Light reviews academic research on dark tourism and thanatourism over 20 years, focusing on definitions, ethical issues, and the differentiation between dark tourism and heritage tourism (Light, D. 2017). He critiques the progress made and identifies future research directions.

The next popular paper in dark tourism research is "Consuming dark tourism: A thanatological perspective" by Stone and Sharpley, where the authors explore dark tourism consumption through a thanatological lens, examining how socio-cultural attitudes towards mortality influence the demand for dark tourism (Stone, P.R. and Sharpley, R. 2008). They propose a model to understand the consumption patterns and motivations of tourists engaging with sites associated with death and disaster.

It is crucial to state that Stone is the author has made significant contribution to the body of research in dark tourism. Almost half of the top ten cited articles were written by Stone. He is the editor of the Dark Tourism Forum. His research interests include the consumption of dark tourism within contemporary society. In 2012, Stone examined how dark tourism mediates the relationship between life and death in modern society (Stone, P.R. 2012). The paper argues that dark tourism sites serve as mediating institutions that help individuals construct meanings of mortality (539 citations).

It is also crucial that there are several review papers among top cited studies. One of them is the work of Rudi Hartmann, who focuses on the management of heritage sites associated with death and disaster, discussing new concepts and research directions in dark tourism and thanatourism (Hartmann, R. 2014). The paper examines the dissonance in heritage tourism management and the geography of memory.

There are two case studies on the list (see *Table 1*). Strange and Kempa compared the tourist experiences at two former prisons, Alcatraz and Robben Island, and discussed the multiple shades of dark tourism (Strange, C. and Kempa, M. 2003). The authors explored how these sites are marketed and interpreted, considering the influence of memory managers and tourist expectations. Foley and Lennon explore dark tourism related to President John F. Kennedy's life and death, focusing on the media's role and the dilemmas faced by curators and staff at related sites (Foley, M. and Lennon, J.J. 1996). The paper examines how assassination sites are present-

Table 1. Top 10 most cited articles in dark tourism research

Article	Year of publication	Journal	Author(s)	Citations	Type of article
A dark tourism spectrum: Towards a typology of death and macabre related tourist sites, attractions, and exhibitions	2006	Tourism: An Interdisciplinary International Journal	Stone, P.R.	1608	Research
Dark tourism	2017	Oxford Research Encyclopedia of Criminology and Criminal Justice	Lennon, J.J.	661	Review
Progress in dark tourism and thanatourism research: An uneasy relationship with heritage tourism	2017	Tourism Management	Light, D.	660	Review
Consuming dark tourism: A thanatological perspective	2008	Annals of Tourism Research	Stone, P.R. and Sharpley, R.	596	Research
Dark tourism and significant other death: Towards a model of mortality mediation	2012	Annals of Tourism Research	Stone, P.R.	583	Research
Dark tourism, thanatourism, and dissonance in heritage tourism management: New directions in contemporary tourism research	2014	Journal of Heritage Tourism	Hartmann, R.	376	Review
Shades of dark tourism: Alcatraz and Robben Island	2003	Annals of Tourism Research	Strange, C. and Kempa, M.	343	Research
JFK and dark tourism: A fascination with assassination	1996	International Journal of Heritage Studies	Foley, M. and Lennon, J.J.	288	Research
Educational dark tourism at an in populo site: The Holocaust Museum in Jerusalem	2010	Annals of Tourism Research	Cohen, E.H.	222	Research
Dark tourism: Morality and new moral spaces.	2009	Channel View Publications	Stone, P.R.	168	Research

ed and interpreted by tourists. This paper was one of the first dark tourism-related studies.

The ninth most frequently referenced article belongs to Erik Cohen, who introduces the term "in populo" to describe dark tourism sites at the population centres of those affected by a tragedy (Cohen, E.H. 2011). The study focuses on Yad Vashem, the Holocaust memorial museum in Jerusalem, and discusses such sites' educational impact and authenticity. One more conceptual article by Stone closes the list of widely cited articles (168 citations). Author delves into the moral implications and ethical challenges posed by dark tourism, exploring how it creates new "moral spaces" for interpreting death and suffering within tourism contexts (Stone, P.R. 2009). It also critically examines the relationship between dark tourism sites, visitors, and the societal representations of mortality.

Top leading journals publishing dark tourism papers

The field of dark tourism, which explores travel to places associated with death, tragedy, and macabre, has attracted great academic interest in recent years. The main engine of this progress is the publication of high-quality studies in the most prestigious journals. These journals provide a platform for scholars to disseminate their findings and shape debates by highlighting emerging trends, theoretical advances, and case studies around the world. Having examined the contributions of these prominent publications, researchers can gain an in-depth understanding of the current state and future direction of dark tourism research. The five leading journals and their H-index is shown in *Figure 5.*

The *Annals of Tourism Research* is the leading journal in publishing dark tourism-related studies, known for its high impact and rigorous selection process. *Tourism Management* is the second most productive journal (22 papers). *Current Issues in Tourism* ranks third in the articles published on dark tourism. The *Journal of Heritage Tourism* (16 papers) and *Tourism Geographies* (12 papers) round out the top five, highlighting their contributions to the field with a substantial number of published papers. Notably, the leading two journals are published by Elsevier, whereas the other three by Taylor & Francis.

Keyword analysis and categorization of the articles by topics

We analysed the articles based on the keywords to define the popularity of research topics within dark tourism. NVivo analytic software was used to produce a word cloud of the list of keywords from all articles *(Figure 6).* The words in orange were the most often used: dark tourism, experience, death, war, and heritage. All of the words below are closely related to the topic of the review paper. They describe the essence of the articles on dark tourism.

Because one of our main aims with this article was to categorize research on dark tourism, we created a different categorization compared to Light's (2017) analysis which gives a more comprehensive mode to understand research made on dark tourism and highlights several research gaps. The reason for the changes is on the one hand, that new categories emerged from studies published following Light's review of the dark tourism literature. On the other hand, recent literature also identified previously unused categories.

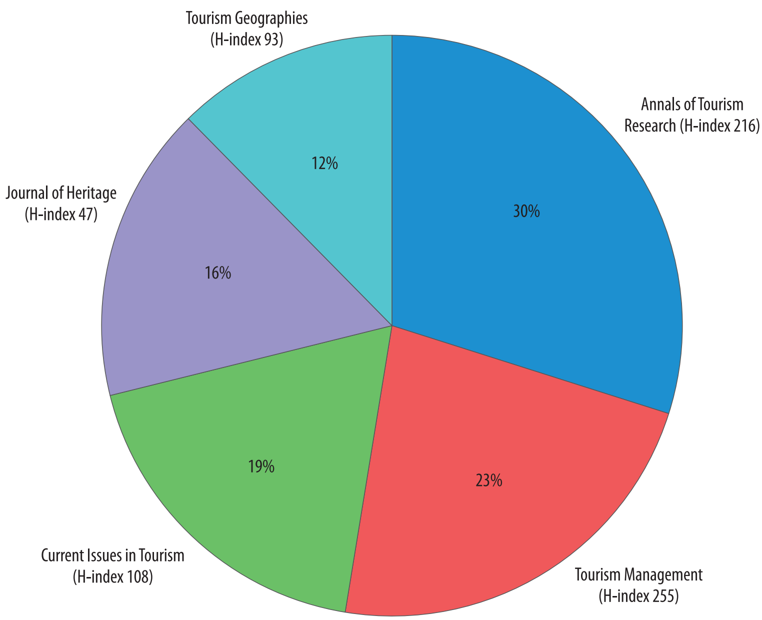


Fig. 5. Leading journals in publishing research on dark tourism (top 5). *Source:* Elaborated by the authors.

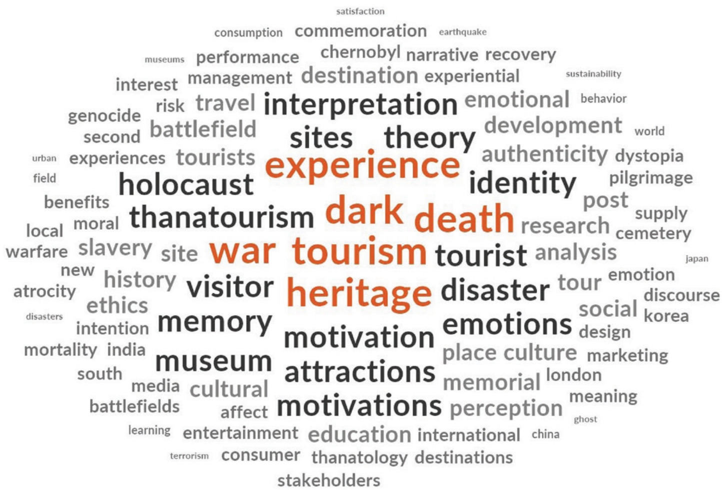


Fig. 6. Word cloud of the keywords in the studies in this review. *Source:* Elaborated by the authors.

Finally, the number of previous categories was too high, and different scales and logic were applied. For example, some categories were defined based on a single event, while others included multiple events and locations that were connected thematically. We present the findings in *Table 2*. To save space, we do not list every article that fits in a category. It is also essential to highlight, that an article can be classified into multiple categories.

Before we began our review, an important issue was what would constitute the initial requirements for considering a paper topic in a particular category; we determined that a category required at least five papers. One category, the role of social media in dark tourism, contained only four papers. However, social media has a crucial role in the modern world, and emerging research direction, so we considered it equivalent to the other categories. Another significant matter that arose because – as we mentioned above – some articles could be included in more than one category. We were interested in the interconnections that answer to the actual core ideas and what drives the research of dark tourism literature. Therefore, we created a connection web. *Figure 7* visually presents the connections among the papers studied in this review. We agreed to place a paper with two multiple possible categories into just one if the core words in that category were mentioned in the article's topic; if the list of keywords contained core words from both categories, we considered the article to be in both categories.

Keywords from the titles and abstracts of the research papers were analysed to determine any interconnections between the categories mentioned before. It was crucial to show that the topics are interrelated to explain the dark tourism processes widely. According to the analytical framework, the connections web illustrates that the 4E (experience, emotion, education, and entertainment) have central arrangements among the topics. The strongest connections can be observed between motivations and experience. Further, war and memory are often connected. Not surprisingly, the most frequently analysed topics have more connections to other categories.

Discussion

As stated in *A review of dark tourism studies* section, although there were attempts to categorize published articles on dark tourism by research topic; further analysis was

Table 2. Categorization of the literature by subtopics of dark tourism

Subtopic	Number of studies	Author(s) and the year of publication
Cemetery dark tourism*	9	Lennon, J.J. and Seaton, A.V. 2004; Levitt, L. 2012; Laws, C. 2013; Sion, B. 2014; Seaton, A.V. 2015; Brown, L. 2016; Mionel, V. 2020.
Communist dark tourism**	7	Lennon, J.J. and Foley, M. 1999; Volcic, Z. *et al.* 2014; Frank, S. 2016; Mileva, S. 2018; Tiberghien, G. and Lennon, J.J. 2019; Ivanova, M. and Buda, D.M. 2020; Lennon, J.J. and Tiberghien, G. 2020, 2021; Schneider, A. *et al.* 2021.
Dangerous zones*	21	Siegenthaler, P. 2002; Goatcher, J. and Brunsden, V. 2011; Stone, P.R. 2013a; Yankovska, G. and Hannam, K. 2014; Cave, J. and Buda, D.M. 2018; Hryhorczuk, N. 2019; Bakota, D. *et al.* 2020.
Dark tourism related to natural disasters*	9	Buissink, N. and Croy, G. 2005; Rittichainuwat, N. 2008; Robbie, D. 2008; Pezzullo, P.C. 2009; Rucińska, D. 2016.
Educational dark tourism**	10	The Shoah (Holocaust Cohen, E.H. 2011; Oren, G. and Shani, A. 2012; Stone, P.R. 2013b; White, L. and Frew, E. 2016; Lennon, J.J. and Teare, R. 2017; Nhlabathi, S.S. and Maharaj, B. 2020.
Emotions in dark tourism**	27	Podoshen, J. 2013; Dermody, E. 2017; Cave, J. and Buda, D.M. 2018; Martini, A. and Buda, D.M. 2018; Nawijn, J. and Biran, A. 2019; Zheng, C. *et al.* 2019; Bertoldi, D. *et al.* 2020; Bull, A.C. and De Angeli, D. 2020; Driessen, S. 2022.
Ethics in dark tourism**	10	Carr, G. 2010; Biran, A. and Hyde, K.F. 2013; Fisher, J. and Schoemann, S. 2018; Martini, A. and Buda, D.M. 2018; Korstanje, M.E. 2019; Šuligoj, M. 2019; Bertoldi, D. *et al.* 2020.
Experience in dark tourism**	50	Yan, B.-J. *et al.* 2016; Zheng, C. *et al.* 2016; Boateng, H. *et al.* 2018; Weaver, D. *et al.* 2018; Langhof, J.G. and Güldenberg, S. 2019; Song, Z. *et al.* 2019; Cui, R. *et al.* 2020.
Genocide tourism*	18	Lennon, J.J. and Malcolm, F. 2002; Hughes, R. 2008; Simic, O. 2009; Moffat, R. 2010; Causevic, S. and Lynch, P. 2011; Friedrich, M. and Johnston, T. 2013; Hohenhaus, P. 2013; Koleth, M. 2014; Sharpley, R. 2014; Sion, B. 2014; Isaac, R.K. and Çakmak, E. 2016; Carrabine, E. 2017; Becker, A. 2019.
Ghost tours*	10	Garcia, B. 2012; Heidelberg, B.A.W. 2014; Ironside, R. 2018; Findlay, J. 2019; Langhof, J.G. and Güldenberg, S. 2019; Weston, G. *et al.* 2019; Dancausa, G. *et al.* 2020.
Memory (commemorative) dark tourism**	33	Hohenhaus, P. 2013; Forsdick, C. 2014; Plominski, A. 2017; Hassapopoulou, M. 2018; Sawczuk, M. 2020; MacCarthy, M. and Heng Rigney, K.N. 2021; Šuligoj, M. and Kennell, J. 2022.
Motivations in dark tourism**	30	Ward, A. and Stessel, A. 2012; Tang, Y. 2014; Zheng, C. *et al.* 2016; Allman, H.R. 2017; Lennon, J.J. and Teare, R. 2017; Podoshen, J.S. 2017; Korstanje, M.E. 2019; Wang, S. *et al.* 2019; Çakar, K. 2020; Mitchell, V. *et al.* 2020; Su, D.N. *et al.* 2020.
Postcolonial dark tourism**	5	Carrigan, A. 2015 Carrigan, A. 2015.; Choung, E. and Choi, S. 2020.
Reviews on dark tourism**	7	Stone, P.R. 2013b; Hartmann, R. 2014; Light, D. 2017; Pliakas, T. 2017; Dhatrak, S.P. 2020; Moisés, J. *et al.* 2020; Naeem, N. and Rana, I.A. 2020; Lim, S. and Kim, J. 2023.

Table 2. *Ccontinued*

Subtopic	Number of studies	Author(s) and the year of publication
Slavery-related dark tourism*	17	Austin, N.K. 2002; Ashworth, G.J. 2004; Beech, J. 2008; Dann, G.M.S. and Potter, R.B. 2008; Yankholmes, A.K.B. 2009; Yankholmes, A.K.B. and McKercher, B. 2015.
Social media role in dark tourism**	4	Zerva, K. 2017; Bertoldi, D. *et al.* 2020; Navickiene, R. *et al.* 2020.
Suicide/crime-related dark tourism**	20	Preece, T. and Price, G. 2006; Best, M. 2007; Kang, E.-J. and Lee, T. 2013; Sion, B. 2014.
Terrorism**	6	Sönmez, S.F. 1998; Fyall, A. *et al.* 2006; Korstanje, M.E. and Clayton, A. 2012; Seraphin, H. 2017; Isaac, R. 2018.
War/conflict tourism*	78	Sharpley, R. and Stone, P.R. 2009; Bigley, J.D. *et al.* 2010; Braithwaite, R. and Leiper, N. 2010; Carr, G. 2010; Chronis, A. 2012; Cheal, F. and Griffin, T. 2013; Seaton, P. 2019.
Dark associated with Holocaust*	23	Lennon, J.J. and Foley, M. 1999; Keil, C. 2006; Kaelber, L. 2007; Beech, J. 2010; Biran, A. *et al.* 2011; Cohen, E.H. 2011; Allar, K.P. 2013; Isaac, R.K. and Çakmak, E. 2014; Busby, G. and Devereux, H. 2015; Liyanage, S. *et al.* 2015; Podoshen, J.S. 2017.

*Categories adopted from Light, D. 2017, **Categories identified by the authors.

needed in this direction. This study offers several distinctive contributions compared to prior reviews of publications on dark tourism. First of all, it provides a more up-to-date analysis, encompassing themes and trends that have surfaced recently. The paper offers a comprehensive, coherent framework that considers recent advancements in the discipline by methodically classifying research subjects beyond specific events or places. It also provides a more inclusive viewpoint by highlighting significant geographical and thematic gaps, such as the underrepresentation of regions like post-communist countries (Patrichi, I.C. 2013; Mileva, S. 2018), Africa, and Latin America. To demonstrate interdisciplinary opportunities and the possibility of further investigation, the study also graphically depicts the thematic linkages among dark tourism subjects (see *Figure 7*).

Our aim was to create a categorization that includes the new topics and does not establish categories based on a single event or location. On our own, we identified 20 categories from among 428 studies. Generally, we found that mass publication in dark tourism research started in earnest in 2011 and increased extensively after 2016. According to Buckley, R. (2012) and Light, D. (2017), themes such as definitions and scope of dark tourism, ethical debates, collective memory issues, motives for visiting dark spots, and visitors' experiences were the highest research priority between 2006 and 2016. A very high-priority topic emerged during our research on dark tourism: war and conflict zones. Current conflicts such as the ones in Israel and Ukraine will change the state of affairs when they end, but we do not have clear evidence for new destinations and directions in dark tourism. However, we believe it is likely that Bucha and Azovstal are potential destinations for dark tourism in the category of war zones where human rights were violated.

Following Duncan Light's influential work in 2017, several reviews have further explored emerging trends and gaps in dark tourism research, which could add signifi-

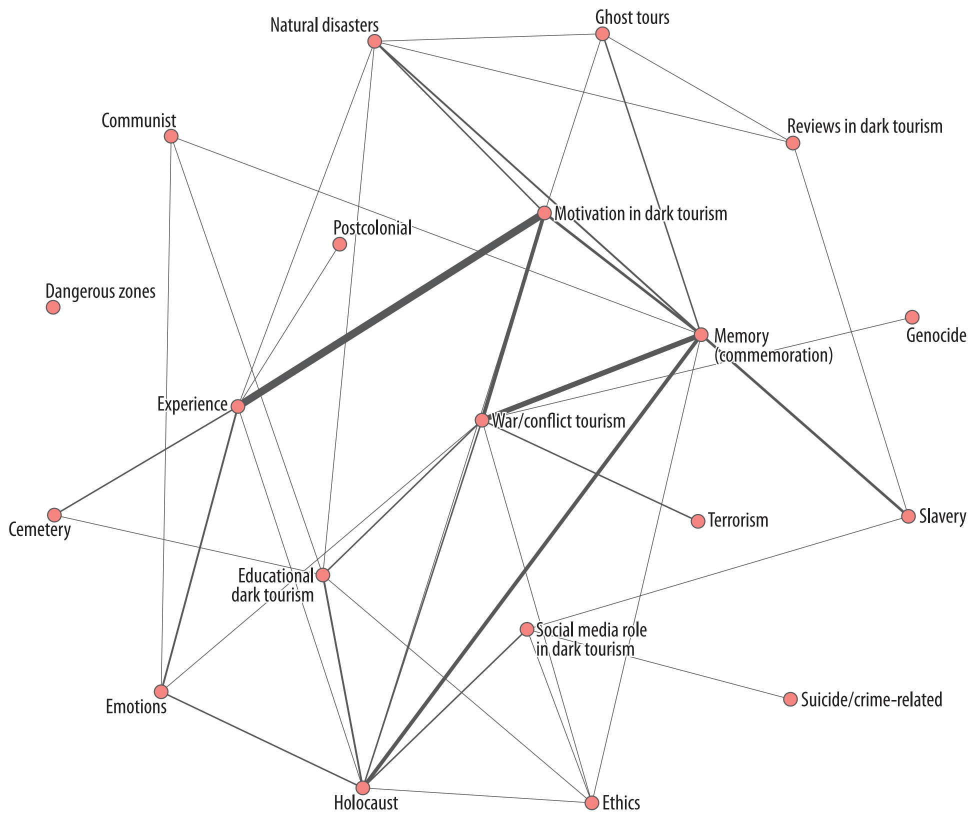


Fig. 7. Connection between categories of dark tourism. *Source:* Elaborated by the authors.

cant depth to this manuscript. For instance, a bibliometric study on the evolution of dark tourism was presented by Mora Forero, J.A., Nieto Mejia, J. and León-Gómez, A. (2023), with particular attention to the reasons behind tourist visits, moral dilemmas, and the cultural significance of locations connected to tragedy and death. This study shows that there is a growing interest among academics in comprehending the ethical issues of dark tourism, especially when it comes to places like concentration camps and disaster sites (Mora Forero, J.A. *et al.* 2023). Expanding on this, Shekhar and Valeri (2022), who looked at the study trajectory of dark tourism, there was a noticeable surge in publications during the COVID-19 pandemic, which suggests that themes of mortality and memorialization are becoming a growing trend. This paper additionally stresses knowledge clustering and network analysis in dark tourism research, mapping academic collaboration with tools like Sci2 and Gephi. Shekhar and Valeri also emphasized the significance of investigating dark tourism's sociocultural, psychological, and ethical aspects and advocated for greater regional and cultural variety in the industry (Shekhar, A. and Valeri, M. 2022).

In analysing the categories by the keywords used, the categories identified by previous studies were the most popular. Visualizing the connection between the categories also highlights possible research directions, and the combinations of multiple categories could enable us to grasp the complexity of dark tourism. Furthermore, the underrepresentation of postcolonial or post-socialist studies is also reflected in the thematic connections since these categories are not embedded in the wider net of topics.

One of the essential aims of this paper was to identify research gaps in the literature on dark tourism (Borén, T. and Gentile, M. 2007). Generally, identified gaps can be divided into three groups of understudied topics. First of all, there are territorial gaps. *Figure* 3 shows countries with no dark tourism studies (coloured in grey). Historically, there has been tremendous suffering in Africa, Latin America, and Central Asia, and these areas offer many sites for dark tourism. For instance, Africa can be studied in the context of slavery tourism, which has been explored in numerous studies. Scholars like Yankholmes and McKercher have extensively examined slavery heritage in Ghana (Yankholmes, A.K.B. and McKercher, B. 2015), alongside other studies focusing on the representation and remembrance of slavery across various heritage sites (Beech, J. 2008; Yankholmes, A.K.B. 2009; Mowatt, R.A. and Chancellor, S.H. 2011).

Latin American states could be case studies for tourism in dangerous postcolonial zones, and Central Asia and Eastern Europe historically are the cores of post-socialist and communist frames of reference (Cristiana, P.I. 2013; Mileva, S. 2018; Schneider, A. *et al*. 2021) based on factors such as built environment, exploitation, violation, and conquering. The second group of gaps can be called topic gaps (analytical framework gaps). We identified the following topics as little seen in the current research body: postcolonial context in dark tourism (Carrigan, A. 2015), use of communist heritages in dark tourism (Borén, T. and Gentile, M. 2007; Mileva, S. 2018), terrorism-related research, and social media links have not been elucidated insufficiently. Thirdly, interconnections shown on the connections web would be helpful to observe which topics are poorly studied in an interdisciplinary manner.

By showing how locations connected to trauma, humiliation, or conflict can produce or reinforce conflicting memories and narratives, Ashworth's work has been essential in exploring the function of "dissonant heritage" in dark tourism (Ashworth, G.J. 2008). His studies of dark heritage and slavery heritage broaden our knowledge of how challenging histories are portrayed and understood for various audiences, which can enhance our examination of heritage tourism in postcolonial settings and conflict areas. Since Ashworth highlights the management of intricate historical narratives at dark tourism sites and raises the possibility of education and reconciliation, this viewpoint meets the gaps in our study (Ashworth, G.J. and Hartmann, R. 2005).

Due to the complex meanings of dark tourism, extending analyses to these understudied regions and topics could benefit education on the events and provide the basis for a shared understanding and commemoration. To this end, an increasing role of internal authors would be also beneficial to fulfil the potentials (emotions and experiences, education and entertainment) of dark tourism.

Dark tourism connects interdisciplinary directions regarding its touristic and service object qualities. According to Isaac, R.K. (2022), this is an emerging subject in the analysis of dark tourism, but further research is needed to grasp the various types of visitors and experiences and the diversity of meanings associated with tragic events. Our study supports this statement by highlighting regional and thematic gaps in the existing body of literature.

Conclusions

Dark tourism is an intangible product aimed at commemorating and co-creating knowledge. It is an essential tool in cooperative education because evolving popularity allows forgotten history to be revised and transferred to the public. With this paper, we demonstrated a considerable gap in the research on the dark tourism industry, and we offer unique ideas concerning tourism development. By highlighting this issue, we hope this research will provide future potential study topics. As highlighted in the discussion part, several development pathways offer unique ideas concerning tourism development, but these are not being addressed in the literature: For example, speaking about death camps, forced labour camps, and other dark events in East European and Central Asian countries is crucial, and dark tourism with communist heritage and postcolonial context is less studied. It would not only provide valuable contributions to the scientific work on the topic but could also contribute to wider social and political aims.

This paper's main empirical contribution is mapping the most common dark tourism study themes and identifying their interconnections. Our updated classification of dark tourism research offers a framework for comprehending the field's changing geography. Further investigation into the relationships between dark tourism and social, cultural, and political goals is also encouraged by this article, especially in post-conflict and post-communist settings.

It is important to highlight the primary limitation of this paper, which is that we only searched one term "dark tourism"; we would have inevitably retrieved more articles if we had used more search terms. So far, there are only a few reviews on overall dark tourism studies, thus, our reference point was Duncan Light's (2017) prototype; we revised the existing categorization and analysed the connections between research topics. The main contributions of this research are the following: the most often discussed research topics and their connections are identified, and the uneven geography of the studies is highlighted. Based on these findings, several possible directions for future research are indicated. Besides the above, another possible study topic concerns the circumstances around the emergence of the novel coronavirus infection. As is known, the first person infected with COVID-19 was identified in Wuhan, Hubei Province, China. Experts claim that the illness was traced to Wuhan's wet market (Le Page, M. 2021; Xiao, X. *et al.* 2021). Considering this background, Wuhan could be viewed as a possible dark tourist site – creating a new category: pandemic-related destinations.

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Exploring new dimensions of urban governance: The development of administrative systems in Trieste and Fiume (Rijeka) during the final decades of the Habsburg Empire (1850–1918)

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Abstract

Urban governance is often perceived as a concept that has emerged over the past half-century, evolving from the policy of urban government. The analysis of this shift, known as the "transformation thesis," has been criticized by recent studies in the field, which focus on the theory of metagovernance. However, both branches of urban governance literature heavily rely on knowledge of American cities, hindering a comprehensive understanding of the phenomenon. There is a growing demand to broaden the temporal and geographical scope of case studies and conduct more comparative research to better understand the roots and current processes of urban governance. While the fundamental driving forces behind the emergence of modern municipal administration during the 19th century have been adequately explored, various characteristics of different geographical locations might add new dimensions and approaches to understanding urban governance. This study offers a comprehensive insight into the birth and early formation of urban governance systems in the free ports of the Austro-Hungarian Monarchy, namely Trieste and Fiume (Rijeka in Croatian). By analyzing legal documents and applying a mixed-method approach, this study unravels the institutional structures, electoral systems, and municipal authorities of Trieste and Fiume from the 1848 Revolution until the end of the First World War. In addition to the historical and Central European perspectives, this paper aims to explore rarely considered contextual factors of urban governance, such as legal-administrative, socio-economic, and political elements. The comparative analysis of Trieste and Fiume demonstrates that even within the same empire, a wide range of diverse influences could shape urban governance systems. Despite these varied factors and significantly different administrative contexts, surprisingly similar governance practices could also emerge.

Keywords: Austro-Hungarian Monarchy, Trieste, Fiume (Rijeka), urban governance, metagovernance, legal geography, historical geography

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Introduction

Urban governance theory still has many "black gaps" in its empirical background, leading to an unclear definition of the phenomenon. Urban case studies related to the theory have been conducted for nearly half a century since the oil crises in the 1970s triggered a radical change in the governance of American cities, shifting from a managerial to an entrepreneurial approach (Harvey, D. 1989). This shift has long been the focus of researchers' attention and was later termed "transformation thesis" (Lo, C. 2017). Recently, another approach within urban governance theory has emerged: the concept of metagovernance, which briefly refers to *"... the governance of governance networks"* (Berg-Nordlie, M. 2018, 51).

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Researchers studying metagovernance have begun to call their works the "second generation" of urban governance literature, highlighting a shift in focus within urban governance research (Lo, C. 2017). However, neither the "first" nor the "second generation" of the literature addresses critical research aspects necessary to reach a consensual definition of urban governance. There are clear deficits in information regarding temporal and spatial scopes, particularly concerning the birth of modern urban governance and its circumstances from a non-American and non-British perspective. More and more researchers in the field are suggesting broadening the scope of case studies in terms of time and geography to better understand the current processes of urban governance and the historical paths that led to them (Pierre, J. 2005; Dear, M. and Dahmann, N. 2008; DiGaetano, A. 2009).

The research presented in this paper aims to address and compare case studies that could illuminate some of these "black gaps" in urban governance theory. The late Austro-Hungarian Monarchy, which existed between 1867 and 1918, provides an excellent context for such research, offering valuable insights into the circumstances surrounding the birth of modern urban governance in Central Europe. The unique constitutional and administrative structure of this state presents numerous opportunities to study and compare cities within different administrative contexts, yet all under the realm of a common imperial apparatus. Out of hundreds of urban municipalities in the empire, the most compelling cases regarding the birth of modern urban administrative systems are Trieste and Fiume (now Rijeka), which are the subjects of this paper. These cities were highly autonomous free ports for more than a century at the time of the Austro-Hungarian Compromise of 1867, thanks to privileges granted by the Habsburg dynasty in 1719. Despite a common past, an intriguing rivalry characterized the relationship between Trieste and Fiume, stemming from the complex state structure of the Austro-Hungarian Monarchy. They were the main ports of the same customs area but operated under different national interests, as Trieste was part of the Austrian half while Fiume was part of the Hungarian half of the empire. Furthermore, both cities had a strong Italian ethnic character that dominated their urban governments, adding another layer of complexity to the governance of the ports.

Most literature on the modernization of urban governance systems in the 19th century focuses on public health, security, and issues related to rapid urbanization which altogether induced the emergence of a new kind of urban administrative system. However, it is unquestionable that geographical factors, including different state structures and local socio-economic dynamics, could also impact this process (Hilbert, B. 2024). This study aims to present and compare the birth and early development of Trieste's and Fiume's urban governance systems primarily from a legal-geographical perspective. This means that the study relies exclusively on information from legal documents (patents, decrees, provisional acts, parliamentary acts, etc.) to unravel this pivotal period of administrative reform. The necessary legal documents for this research are available in online databases. Acts passed by the Austrian Parliament (Reichsrat) and the provincial parliament of Austrian Littoral (whose seat was Trieste) between 1850 and 1918 are all available in the online database of the Austrian National Library (Österreichische Staatsbibliothek [ÖNB] ALEX Historische Rechts- und Gesetzestexte). Acts passed by the Hungarian Parliament (Országgyűlés) between 1867 and 1918 are also accessible online at *net.jogtar.hu*. However, imperial patents and government decrees regulating the municipal administration of Fiume were not included in this database but can be found in a digital appendix of a Hungarian book (Gergely, J. 2005). It must be noted that due to the legal-geographical approach, only the logic and content of legal acts will be represented normatively in this research. The analysis of their implementation in practice remains the topic of another scientific study.

Urban governance theories and their (lack of) historic perspectives

The theory of urban governance related to the neoliberal turn starting in the 1970s is relatively new in both geography and public administration science. Research linked to the term governance – extending beyond cities – began in the 1950s, but it truly proliferated in the late 1970s, with studies on the subject steadily increasing ever since. Alongside economics, management, political science, and public administration, geography is also one of the disciplines contributing significantly to the literature on the topic (Levi-Faur, D. 2011). Despite many studies and empirical data, there is still no complete consensus on the definition of the concept, and the delineation of the term can even be considered somewhat confusing (Rhodes, R.A.W. 1997). Rather, it provides an analytical framework or a set of criteria for topics worth researching, which, in its simplest form, primarily focuses on the multitude of institutions and actors determining urban policy and their interactions (Pierre, J. 2005). This is reinforced by the definition of one of the leading researchers in urban regime theory, Clarence Stone, who describes urban governance as an extremely complex, fragmented network of institutions and actors, inherently lacking consensus (Stone, C. 1989).

When placing the concept in a broader context, its meaning becomes far more complex. The main characteristics of urban governance include the economic restructuring prompted by globalization, the retreat of state involvement, the global competition of cities for capital investments, the flexibility and multi-actor nature of decision-making, and partnerships between the state and the private sector (Jelinek, Cs. and Pósfai, Zs. 2013). In contrast, the general urban policy systems before World War II are described as urban government, where *"…the governance of the city existed within a closed, hierarchical institutional framework with a few, well-identified actors, providing certain public services to city residents and translating national redistributive policies to the local level"* (Jelinek, Cs. and Pósfai, Zs. 2013, 145). A lot of researchers of urban governance sharply distinguish these two urban policy systems and draw a clear line between them during the transition period in the 1970s and 1980s, closely linked to the oil crises (Harvey, D. 1989; Osborne, D. and Gaebler, T. 1992; Rhodes, R.A.W. 1997; Stoker, G. 1998; Pierre, J. 1999; Jessop, B. 2002; Brenner, N. 2004; Eckardt, F. and Elander, I. 2009; Slack, E. and Côté, A. 2014; Van den Dool, L. 2015).

More and more studies concerning urban governance are increasingly critical of the research focusing on the shift from urban government to governance, often referred to as the "transformation thesis" (Lo, C. 2017). British experiences suggest that the institutional system of British local governments was quite fragmented and multi-polar in the mid-19th century (Andrew, C. and Goldsmith, M. 1998; Goldsmith, M. and Garrand, J. 2000), making it contemporaneous with urban government itself (Pierre, J. 2005). British historians and political scientists have pointed out that the changes and processes that began in the 1970s – such as private-public partnerships and different modes of providing public services – in urban governance systems cannot be considered entirely novel, as they were identifiable during the industrial revolutions and the formation of nation-states in the 19th century (Morris, J.R. 2000). Based on these insights, Andrew M. Wood's suggestion of reevaluating the theoretical frameworks of the topic is worth considering (Wood, A.M. 2004). Partly responding to the defects of transformation theses, another conceptualization of urban governance has recently in the emergence, centering around the idea of metagovernance, which involves *"... the governance of governance networks"* (Berg-Nordlie, M. 2018, 51). This approach mostly tries to understand the effects of state legislation on the steering of subnational subjects (Bailey, D. and Wood, M. 2017). Studies in this new approach identify themselves as the "second generation" of urban governance literature, but due to their novelty, metagovernance theory also lacks a clear definition and has a wide range of conceptual branches (Gjaltema, J. *et al.* 2019).

However, neither the first nor the second generation of literature on urban governance provides answers regarding the path leading to the formation of modern urban governance from a cross-national perspective (DiGaetano, A. 2009). In addition to the narrow temporal and spatial frameworks of research, several studies have pointed out the lack of comparative analysis in the field (DiGateano, A. and Klemanski, J.S. 1999; Sellers, J.M. 2002; Pierre, J. 2005; DiGaetano, A. 2009; Slack, E. and Côté, A. 2014). Pierre and DiGaetano, in their separate studies, have already identified and connected these defects to the empirical background of urban governance, offering useful suggestions for future case studies on the topic (Pierre, J. 2005; DiGaetano, A. 2009). These suggestions are closely related to the concept of metagovernance, highlighting the role of state legislation and the question of the embeddedness of local governments within the state administration.

The beginning of "modern urban governance" is generally linked to the enactment of laws that established the administrative systems of cities – including institutional structures, electoral systems, decision-making mechanisms, and municipal responsibilities – adopted by democratically elected parliaments rather than imposed by exclusive powers (DiGaetano, A. 2009). These laws first emerged in Western Europe and North America in the early 19th century and later in Central and Eastern Europe in the mid to late 19th century. Literature is scarce on urban governance that specifically examines a city's administrative conditions during this formative period and evaluates their relevance to current theories. Sutcliffe 's work stands out in this regard, as he goes beyond analyzing legal structural changes in cities and situates them within a broader socio-economic context. The British historian primarily examined the urban development and planning activities of large cities in the 19th and 20th centuries, focusing on issues triggered by urbanization – such as unemployment, poverty, crime, and the formation of slums – which necessitated municipal intervention and the expansion of urban authority (Sutcliffe, A. 1995a,b). DiGaetano's study outlines the formation of 19th-century urban governance in Boston and Bristol, linking it to the question of the path leading to 20th- and 21st-century urban governance theories (DiGaetano, A. 2009). In DiGaetano's interpretation, democratization is essentially a consequence of the causes of urbanization and economic diversification, at least as observed in Boston and Bristol. The first and most crucial step in the democratization process was the establishment of municipal laws, which determined the electoral system for municipal governing bodies and the scope of municipal institutions' authority. The governance of cities could be framed by different legal frameworks depending on the state. In the cases of Boston and Bristol, democratization was accompanied by the emergence of problem-oriented urban politics, with the municipal governments initially focusing on the organizational system of local police and the construction of water supply systems. DiGaetano termed the formation of modern urban governance in Boston and Bristol a "municipal revolution," following Teaford's expression (Teaford, J.C. 1975), and characterized it by the gradual expansion of urban institutional authority and the broadening of public services provided by the city. While DiGaetano's research is an excellent example that addresses some of the deficiencies in urban governance theory but remains within the context of the United States and the United Kingdom. There are a few additional examples of urban case studies from a historical viewpoint, which mainly focus on the modernization of urban administrations in light of urban problems (Marcus, A.I. 1980; Fairbanks, R.B. 1999; Hanley, A.G. 2012).

The main theoretical approach and question of the study

Responding to the limitations and gaps in urban governance theories, this study aims to uncover the main characteristics of Trieste's and Fiume's administrative systems during the era of the Austro-Hungarian Monarchy, which spanned from 1867 to 1918. This research seeks to gather empirical information outside the traditional geographical and temporal scope of mainstream literature, employing an analytical framework that combines the main points of both the first and second generations of urban governance literature. Examining the legislative roles of the common emperor and the state parliaments in regulating the administrative systems of the two ports, this study relates to the concept of metagovernance. On the other hand, the analytical practices of the transformation thesis which centered around municipal institutional and authority issues are also taking part in the examination. However, this study aims to go further by incorporating factors that are typically unusual in this type of research: historical, legal, socio-economic, and political factors.

The comparison of the two largest ports of the Austro-Hungarian Monarchy is highly relevant for addressing some of the undiscovered areas of urban governance. There are additional compelling reasons to explore Trieste's and Fiume's administrative structures, which could potentially yield new insights: their special administrative statuses, their complex socio-political scenes, the Italian dominance in their urban administration, and their rivalry for the "gateway" role within the empire. The literature on Habsburg-era Trieste and Fiume is extensive, primarily focusing on ethnic, identity, and economic features (Some examples: Guri, D. 1953; Govorchin, G.G. 1955; Ress, I. 2009; Hajdú, Z. 2013; Makkai, K. 2013; Griffante, A. 2015; Pelles, M. 2017). However, comparative studies of these cities during the Habsburg era are much less common in historical-geographical literature, with only a few comparative works mainly from an economic perspective (Helmedach, A. 2002; Erdősi, F. 2022).

This study aims to fill these gaps while raising new issues and factors that could be integrated into urban governance theory. The following question has been formulated to guide the study's objectives, ensuring its complexity in both approach and methodology: How did the *legal structure of the Austro-Hungarian Monarchy*, as established by the Compromise of 1867, along with the unique intersections of *local historical, socio-economic, and political factors*, influence the early formation of Trieste's and Fiume's urban governance systems in terms of their municipal *institutional structures, electoral systems*, and *legal and financial authorities*?

By addressing the various components of this comprehensive question, the study will undoubtedly provide extraordinary insights compared to the experiences of American cities.

A brief history of Trieste's and Fiume's free port status before 1867

The two most important seaports of the Austro-Hungarian Monarchy, located by the shores of the opposite gulfs of the Istrian Peninsula, had always been situated at the boundaries of spheres of interest throughout history. Due to their economic potential, these cities achieved a certain degree of autonomy, often manifested in their autonomous administrative statuses (Pelles, M. 2017). The ports, founded by the Romans, had long competed with each other and with different ports of the Adriatic Sea. In the Middle Ages, Venice was their most significant rival until the Habsburg Empire began expanding in the region. Trieste became part of the Habsburg Empire in 1382, and Fiume after the Battle of Mohács in 1526 (Govorchin, G.G. 1955). The Habsburgs recognized the economic opportunities in maritime trade relatively late, only during the 18th century. Due to its geographical proximity to Vienna, the royal government supported the development of Trieste earlier and more vigorously, with the main goal of making it the focal point of trade between Europe and Asia (Griffante, A. 2015). Fiume's development stagnated for a while, but later the Habsburgs realized that developing Fiume could bolster the economic life of the empire's lagging eastern part (Ress, I. 2009). In 1719, Charles VI (known as Charles

III in Hungary) declared both Trieste and Fiume free ports and ordered significant developments (Hajdú, Z. 2013; Ordasi, Á. 2019). While Trieste's administrative situation stabilized within the empire, Croatian and Hungarian aspirations for the possession of Fiume intensified. In 1775, the municipal council initiated the annexation of the settlement to Hungary, which was partly realized by queen Maria Theresa's patent on the annexation to Croatia in 1776. However, due to emerging Hungarian dissatisfaction, she declared it a "separate body attached to the Hungarian crown", also known as corpus separatum, in her 1779 charter (Hajdú, Z. 2013). The Act IV of 1807 eventually stated that Fiume's representatives would have seats in the Hungarian Diet, effectively placing the city under Hungarian jurisdiction.

During the Napoleonic Wars, the administrative paths of the two cities briefly diverged as Napoleon annexed Trieste to the Kingdom of Italy and Fiume to the Kingdom of Illyria (Guri, D. 1953; Hajdú, Z. 2013). After the ports were reunited under the Habsburg realm, the Italian elites headed the ports faced new challenges in the wake of national movements during the 1848 revolutions. While Trieste became a main target of the Slovenian national movement, Fiume found itself at the center of Croatian-Hungarian conflicts for several decades. After the revolution, both Trieste and Fiume received statutes establishing their municipal administrations. However, the Austrian port received a much more detailed statute as the seat of the Crownland Austrian Littoral that remained in effect until 1918, stabilizing the city's administration for decades. Fiume's situation plunged into complete uncertainty. After the suppression of the Hungarian Revolution, the Habsburgs annexed the port to Croatia, which initially became a de facto crownland of Austria while Hungary was ruled by military administration (Sokcsevits, D. 2011).

However, with the political changes of the Austro-Hungarian Compromise in 1867, Fiume's leaders unequivocally advocated for annexation to Hungary (Hajdú, Z. 2013). The negotiations devolved into an eighteen-month-long, fruitless debate between Croatian, Hungarian, and Fiume municipal representatives. Finally, the Hungarian government "solved" the situation in a rather unfair way, which became known as the "Rijeka Patch" in Croatian historiography. When the Croatian Parliament (Sabor) enacted the Croatian-Hungarian Settlement of 1868, later assented to by the emperor, the Hungarian government only discussed it afterward and added a clause on a slip of paper to the paragraph stating the undefined status of Fiume. This clause annexed the port to Hungary without the knowledge of the emperor and the Sabor (Sokcsevits, D. 2011). This affair intensified the opposition between Hungary and Croatia-Slavonia for decades to come.

The administrative structure of the Austro-Hungarian Monarchy, established by the Compromise of 1867

The Austro-Hungarian Compromise of 1867 created a highly unique state structure where "common affairs" which included military, foreign, and financial matters connected mainly Austria and Hungary to each other. This agreement established joint state institutions, such as ministries for each common affair, delegations from both Austrian and Hungarian parliaments, and a common council of ministers headed by the emperor. The constitutions of Austria and Hungary defined the jurisdiction of these common bodies in a "negative form," indicating that they could not interfere in the internal affairs of either half of the empire. Nevertheless, there were occasions when internal matters of Austria or Hungary were addressed within these joint institutions (Somogyi, É. 1996). As a result, the empire's state structure was somewhat between a federal state and a confederation: within a single customs area two separate administrative systems coexisted, and both state governments were engaged in various shared responsibilities. Within this customs area, the free movement of labour, services, goods, and companies was allowed, and a common official currency was in use (Szente, Z. 2011; Katus, L. 2012).

Beyond the historical traditions of both Austria and Hungary regarding their state structures, the role of the common emperor significantly influenced the distribution of power across different administrative levels. According to the Compromise of 1867, Emperor Franz Joseph retained near-absolute authority in the legislative process in both parts of the empire, allowing him to maintain the status quo of the dualist state structure (Sarlós, B. 1976). In Austria, the emperor could govern through emergency decrees without needing the consent of the Austrian parliament (Reichsrat). Consequently, there was no real possibility for any opposition party to threaten the status quo in the Reichsrat, which enabled a broader distribution of power to the crownlands and the municipalities. In contrast, the Hungarian legislative process granted the emperor only the right of pre-Royal assent. This did not afford him the same absolutist power as in Austria, requiring him to negotiate and reach agreements with the Hungarian government and the Hungarian Parliament (Országgyűlés). This arrangement concluded with the thorough centralization of the Hungarian administrative system to eliminate any possible internal opposition, which resulted in the reduction of the authority of subnational subjects (Sarlós, B. 1976).

The division of municipal governments and their integration into the respective administrative systems differed fundamentally between Austria and Hungary *(Figure 1).* The Austrian Act on Municipalities of 1862 (AA, 1862), as a federal law, specified basic regulations for Austrian municipalities but allowed the crownlands' parliaments to tailor these regulations to their provincial contexts. Larger municipalities could obtain statutes from provincial parliaments, granting them expanded jurisdiction over institutional and financial matters to better manage municipal tasks. Hungarian urban municipalities were divided into four categories according to Hungarian administrative laws (HA, 1872a,b; HA, 1886a,b): Municipal

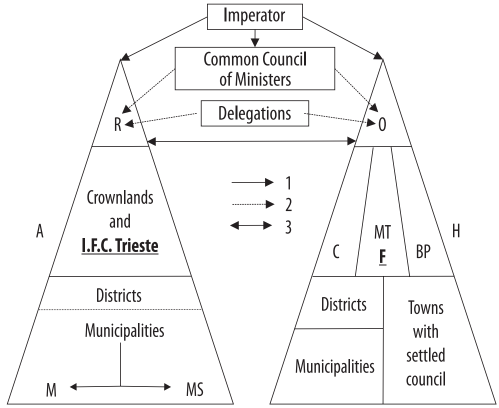

Fig. 1. Schematic representation of the Austro-Hungarian Monarchy's administrative structure and the positions of Trieste and Fiume (marked in bold and underlined font). 1 = direct influence; 2 = indirect influence; 3 = common and jointly managed matters, as well as negotiation of the customs union. **A** = Austria: R = Reichsrat (Austrian Parliament), I.F.C. Trieste = Imperial Free City of Trieste (Reichsunmittelbare Stadt Triest und ihr Gebiet), M = Municipalities, MS = Municipalities with Statute. **H** = Hungary: O = Országgyűlés (Hungarian Parliament), C = Counties, MT = Municipal Towns (towns with county rights), F = City of Fiume, BP = Budapest. *Source:* Author's elaboration based on Brauneder, W. 1994, and Mezey, B. 2004.

Towns (with county rights), Towns with settled councils (under county supervision), and Budapest and Fiume, which had their own statutes. Croatia-Slavonia gained autonomous status in 1868, which included the regulation of internal administration. However, the division of Croatian urban municipalities largely mirrored the Hungarian model: there were towns with county rights and towns with district rights (Čepulo, D. 2010).

The administrative positions of Trieste and Fiume within the Austro-Hungarian Monarchy and their respective halves of the empire shared several similarities: both cities had unique statutes granted by the 1850 statute of Trieste and the 1872 statute of Fiume, which was practically modeled after the former (Ordasi, Á. 2019). They retained their status as free ports, with Italians having primary control over their administration. Trieste became a city "directly subordinated under the empire" (Reichsunmittelbare Stadt), meaning it was under the supervision of the emperor and the Austrian Parliament (AA, 1850; Griffante, A. 2015). Similarly, Fiume came directly under Hungarian parliamentary legislation (see *Figure 1*), and both cities were entitled to send representatives to their respective parliaments (HA, 1872a). The status of Trieste and Fiume changed significantly in 1891 when the two cities were integrated into the Monarchy's customs territory, abolishing their tax-free zones that had existed since 1719 (AA, 1891; HA, 1891). Neither the basic statute of Trieste and Fiume was modified fundamentally until 1918. Only minor paragraphs of Trieste's statute of 1850 were modified (AA, 1882; AA, 1885; AA, 1908; AA, 1910) while the Hungarian government through its orders modified significantly the governance of Fiume (HA, 1901; HA, 1913; HA, 1916).

Political and socio-economic dynamics during the era of dualism (1867–1918)

Considering the ethnic diversity and autonomous statuses of Trieste and Fiume, it is crucial to examine the broader context of ethnic agreements within the Austro-Hungarian Empire to fully comprehend the situation of these ports. The Compromise of 1867 established and solidified the dualist system within the Habsburg Empire, but it did not preclude the establishment of territorial autonomies or agreements without altering the Compromise itself. Excluding Bosnia-Herzegovina, a total of four provincial and three municipal-level agreements were reached during the period of dualism *(Figure 2).*

Croatia-Slavonia was the only territory with legally guaranteed de jure autonomy, granting the Croatian Parliament (Sabor) the authority to manage internal administration, cultural and educational matters, as well as the use of the Croatian language in public administration (Sokcsevits, D. 2011). However, the Sabor remained highly dependent on the Hungarian Parliament both politically and financially, allowing Hungarian governments to pursue a centralization policy regarding Croatia-Slavonia. This led to significant changes in Croatian administration and urban governance (Hilbert, B. 2024). In contrast, Galicia's de facto autonomy in Austria was based on concessions that favoured the Poles over the Ruthenians in the governance of the crownland (Perényi, J. and Kovács, E. 1986). Despite this, the Ruthenians were also granted some concessions, including the establishment of a Ruthenian University in Lemberg (Mick, C. 2019). In 1914, an act divided the Galician Diet into Polish and Ruthenian sections, significantly improving the latter's representation, but the outbreak of World War I prevented the implementation of this system (Zöllner, E. 1998). Beyond Croatia-Slavonia and Galicia, efforts to resolve ethnic conflicts were primarily seen in Austria. Agreements in Moravia and Bukovina established the division of their provincial diets into national sections and recalibrated electoral districts accordingly (Kuzmany, B. 2016). An unusual agreement was also enacted in 1914 in a Bohemian municipality, where the German and Czech leaders of Budweis agreed on a new municipal electoral system based on national sections. The Budweis system went further than the provincial agreements by proposing the division of the city's tax revenues into two parts, managed by the respective nationality representative groups, mainly for cultural matters. Although the Budweis Compromise was never realized due to World War I, it demonstrated the potential for resolving nationality issues at the municipal level (Kuzmany, B. 2016).

Trieste and Fiume also held special statuses within the Austro-Hungarian Empire, though their unique roles were driven more by economic factors than by ethnic considerations. Between 1867 and 1918, the increasing intersection of ethnic and power conflicts began to significantly influence public politics in the ports. The dynamic change in the ethnic composition of their population played a

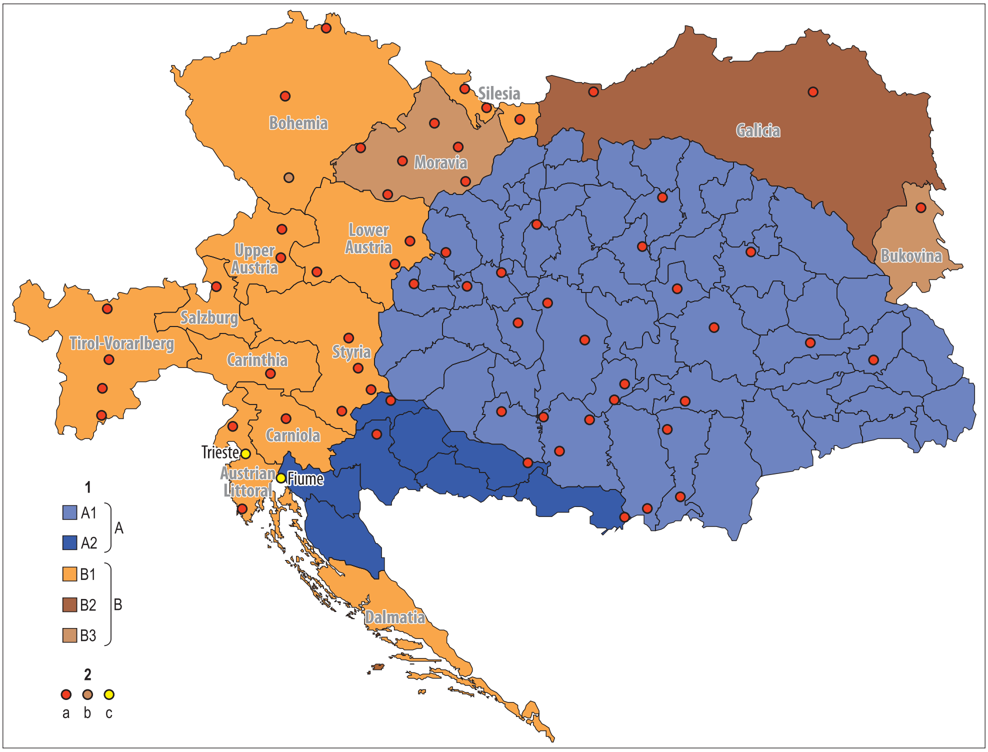

Fig. 2. The administrative divisions, autonomous territories, and other subnational agreements within the Austro-Hungarian Monarchy (1914). **1** – Administrative units of the Austro-Hungarian Monarchy. A = countries of the Hungarian Crown: A1 = Hungary and its county system, A2 = Croatia-Slavonia and its county system. B = crownlands of Austria: B1 = crownlands with their own parliaments and governments, B2 = the "de facto" autonomy of the Crownland of Galicia, B3 = provincial agreements on national electoral rolls; **2** – Municipalities with special statuses. a = municipalities with statutes in Austria, and municipalities with county rights in the countries of the Hungarian Crown, b = agreement on national electoral rolls in the municipality of Budweis; c = free ports of Trieste and Fiume. *Source:* Author's elaboration based on Brauneder, W. 1994, Mezey, B. 2004, and Kuzmany, B. 2016.

significant role in this. The share of the Italian inhabitants in Trieste decreased from 65 to 51 percent between 1880 and 1910, while the Slovenian population increased from 14 to 25 percent. Meanwhile, in Fiume, the Italian population slightly increased from 43 to 48 percent, whereas the Croatian population plummeted from 38 to 25 percent. Notably, the Hungarian population in Fiume surged from 2 to 13 percent, while the shares of the German population remained stable in both cities (Horel, C. 2023). In light of these statistics, it is not surprising that Trieste's municipal administration faced increasing pressure from the Slovenian national movements while simultaneously Italian secessionist movements got also stronger in the city. Trieste's Italian elites, through municipal regulations, obstructed non-Italian education in the city, which intensified and linked Slovenian and Croatian national movements (Gould, S.W. 1945).

However, the Viennese government managed to control ethnic tensions primarily by maintaining the status quo in the city, while granting several concessions to Slovenians in the crownland of Carniola, where they were the majority (Horel, C. 2023). Fiume, on the other hand, faced significant cultural and political pressure from the Hungarian government which sought to erode Fiume's autonomy and strengthen Hungarian cultural influence in the city. The translation of Hungarian laws into Italian often caused confusion, as it took several months, leaving the Fiume Municipal Council poorly informed about Hungarian domestic affairs and matters concerning the city. The enforcement of the Hungarian coat of arms and flag on municipal buildings further fueled local resentment towards Hungarians (Simon, P.P. 2013). Ultimately, in 1913, the Hungarian government through the enactment of an order abolished Fiume's autonomy, and referring to the failed quorum of the Municipal Council, handing over the absolute power over the whole city to the current governor, István Wickenburg (HA, 1913). The conflict did not subside, as bombs exploded in the Governor's Palace in both 1913 and 1914, but the identity of the perpetrators largely remained unknown (Ordasi, Á. 2018).

In addition to the ethnic factor, further economic and political factors played an important role in the development of Trieste and Fiume. The competition between the two port cities for the "gateway role" of the empire was a crucial point of contention between Austrian imperial and Hungarian national ambitions (Erdősi, F. 2005). The primary goal of developing the entire railway system in Austria and Hungary was to connect Trieste and Fiume to their respective capitals. In this context, the Vienna–Trieste line was completed 16 years earlier, in 1857, than the line connecting Fiume to Budapest, which opened in 1873. This competition began with a notable advantage for Trieste due to early Habsburg support during the absolutist era which Fiume could not surpass later on. However, the Hungarian government's efforts led to a substantial increase in Fiume's port cargo traffic (Erdősi, F. 2022). Trieste primarily competed with Genoa for the central role in Mediterranean trade from Europe but eventually lagged behind the Italian port (Guri, D. 1953).

Urban governance systems in Trieste and Fiume based on legal documents (1867–1918)

Integration into the administrative system and institutional structure

The free port status of Trieste and Fiume, originating in 1719, was a decisive factor in shaping the administrative structures of Austria and Hungary in 1867. Both cities were incorporated into their respective halves of the empire as "corpus separatum" with separate customs areas. Fiume's 1872 statute, which replaced the provisional statute of 1870 (HA, 1870), was largely based on Trieste's 1850s statute (Ordasi, Á. 2019), making their governance systems similar in many respects. Neither Trieste's nor Fiume's statute was significantly modified until 1918, unlike the statutes of several other urban municipalities in Austria and Hungary during that period. In Austria, only Prague, Görz (now Gorizia, Italy), and Trieste had statutes originating from the provisional era (1848–1867) enacted absolutistically by the emperor (Hilbert, B. 2023). The ports' unique statuses manifested differently in their state administrations: Trieste was elevated to a provincial rank in Austria, while Fiume formed a separate municipal category within Hungary. However, neither municipality could fully detach from the legal structure of their respective halves of the empire, significantly impacting their internal institutional systems.

Trieste's institutional framework mirrored other Austrian cities with statutes but included a provincial parliament due to its crownland status, with the municipal decision-making body fulfilling this role *(Figure 3).* Trieste became the seat of the unified crownland of the Austrian Littoral, which comprised the Imperial Free City of Trieste, the crownlands of Görz, and Gradisca, and Istria. A common provincial governor, along with the Reichsrat and the emperor, exercised state supervision over the city. The so-called „Fractionen" were unique urban organs within Trieste's administration, serving as territorial executive bodies that complemented the Municipal

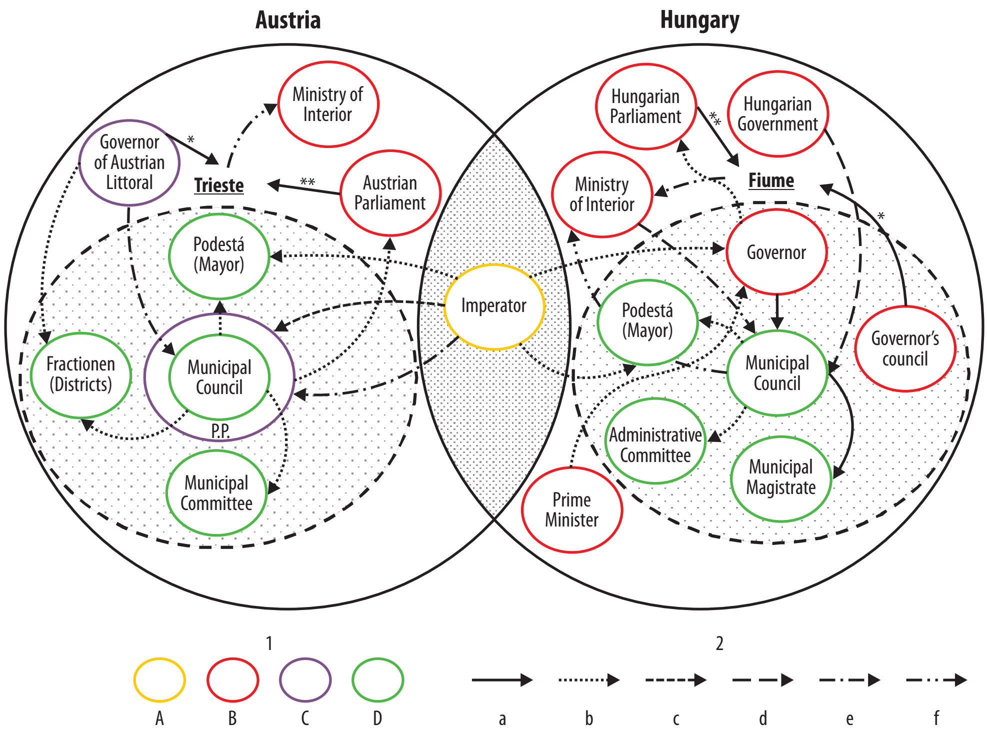

Fig. 3. Schematic figure of the institutional structure of Trieste and Fiume and their positions within the administrative system of the Austro-Hungarian Monarchy in 1914. **1** – Actors involved in urban governance systems: A = The common imperator of Austria-Hungary; B = State body or body appointed by the common imperator and/or the state government; C = Provincial body; D = Body elected by local residents possessed voting rights or body elected by the municipal council. **2** – Official relations between the organs participating in the urban governance system: a – It could uphold, amend and cancel decrees and resolutions, as well as dissolve municipal councils; b = Elected, appointed, consented to the appointment of one or more members; c = It could dissolve a plenum of a body and dismiss an official from his office; d = Before issuing decrees on certain matters, it must consult with the relevant body; e = The body's permission was required for the adoption of certain or all of its decrees; its decisions concerning an appeal or complaint case were binding to the concerned urban organ; f = It could appeal against the decree of another body. P.P. = Provincial Parliament. *The provincial governor/council of governors can suspend the decree or decision of any body in Trieste/Fiume. The Municipal Council could appeal against the decision to the Minister of the Interior. **Since Trieste and Fiume were directly subjected to the state government, they had to apply the laws of their respective parliaments, against which there was no room for appeal. *Source:* Author's elaboration based on the following acts: AA, 1850; AA, 1861; HA, 1870; HA, 1872a; HA, 1901; AA, 1908.

Council. In Fiume, the most significant institutional differences from Trieste were the positions of the Governor and its council which was equivalent to the lord-lieutenants in the Hungarian Municipal Towns and the Lord-Mayor in Budapest. Due to the port's persistent struggle for autonomy, the Governor's and its council's supervisory powers in Fiume were narrower than those of the lord-lieutenants, primarily responsible for communication between the Hungarian government and the municipality. Fiume's statute also included the Administrative Committee, which took on tasks from the Municipal Council and could be granted decision-making power. The complex integration into state administration, along with specific bodies, rendered the governance of the cities fragmented: Trieste had more decision-making and executive bodies, while Fiume had more supervisory bodies (see *Figure 3*).

Electoral system

The electoral systems of Trieste's and Fiume's urban organs showed both similarities and differences in nearly equal measure *(Table 1).* The method of electing members to the cities' representative bodies differed significantly, while the election of the city's mayor (Podestá) was entirely identical. In Trieste, as in other Austrian cities, a curial system was in effect, uniquely operating with four curiae without a tax census for the lowest curia since 1850. Fiume's municipal council's electoral system was completely different, based on a voting register. However, Fiume's election system also differed significantly from that of Hungarian Municipal Towns, as it did not introduce virilism, which allowed the highest taxpayer residents to enter the Municipal Council without a vote.

Another voting instrument absent from Fiume's system was the appointment committee. With a state-elected majority, this committee proposed three nominees for the position of mayor in every Hungarian Municipal Town, from which the municipal councils had to elect one. This organ was a tool of centralization by the Hungarian government (Sarlós, B. 1976). The voting age in Fiume also differed from that in Hungary and was identical to the one in Austria. Although the mayors (podestà) of the two cities were elected in the same way (voted by the municipal committee and assented by the emperor), in Fiume, the Governor was the head of the executive power, appointed by the emperor with the Hungarian Prime Minister's agreement, indicating the city's greater exposure to state control. Nonetheless, the absence of virilism and the appointment committee made Fiume's voting system more democratic than Hungary's and more similar to the Austrian one.

Municipal authority

The special legal status of Trieste and Fiume and their differing integration into their respective state administration systems brought the two port cities closer together regarding their municipal authority (see *Table 1*). Paradoxically, Trieste's elevation to provincial rank significantly limited its municipal powers, as it fell directly under the supervision of the Reichsrat and the emperor. This change required royal assent to establish the municipal institutional system and the adoption of the annual budget which was not the case in other Austrian cities. Fiume also required higher approval for these jurisdictions, but unlike other Hungarian Municipal Towns, issuing building permits and securing local security were solely the rights of the Municipal Council in Fiume, making it more similar to Trieste. Beyond these, the municipal councils of Trieste and Fiume even had a more significant power: the authority to approve any changes to their urban statutes before they were enacted by the state or provincial parliament. This right was not unique across the empire, as Cracow also possessed a similar right (AA, 1866). Both cities could deal with national affairs and could send two representatives to their respective national diets. Additionally, Fiume alongside Budapest and the Hungarian Municipal Towns had a stronger instrument to influence national affairs: the so-called „right to address", allowing the Municipal Council to object to and detain a government order. However, this right was easily eluded by the state government, and after 1901, the expanded jurisdiction of the Governor's Council rendered it ineffective for the Municipal Council (Sarlós, B. 1976). The most significant difference between the port cities' authorities concerned financial matters, specifically regarding the rates of municipal surtaxes, the management of marketable municipal properties, and the terms of borrowable loans. Fiume's Municipal Council did not have the authority to manage these financial matters independently; it required approval from the Minister of the Interior. Trieste had authority over these mat-

Table 1. The main features of the electoral system and municipal authority in Trieste and Fiume compared to Austrian cities with statutes (A.C.S.) and Hungarian Municipal Towns (H.M.T.) (1850–1918)

	A.C.S.	Trieste	Fiume	H.M.T.
Electoral system				
Governor	–		Appointed by the emperor for the proposal of the Hungarian Prime Minister / the Minister of Interior.	
Mayor (Podestá)	Elected by the municipal council which assented by the emperor.			Elected through the appointment committee.
Members of the municipal council	Elected by the local voters in a curial voting system.		Elected by the local voters based on a voting register.	
Members of the Municipal Committee	Elected by the municipal council.			Elected through the appointment committee.
Voting age, year	24			20
Tax census, gulden	Variable (0–25)	–	16	
Virilism	No			Yes
Municipal authority				
Municipal representatives in the state parliaments:	No	Yes		No
Legal right to deal with supraurban matters…	is not allowed.	is allowed indirectly through the municipal representatives seated in the Austrian parliament.	is allowed directly through the „right to address” and indirectly through the municipal representatives seated in the Hungarian parliament.	is allowed directly through the „right of address”.
Approval of the municipal council to change urban statute by the state/provincial parliament…	is not needed. (except Cracow)	is needed. (The municipal council of Trieste could also initiate a modification of the statute through the provincial parliament.)		is not needed.
Approval of a higher administrative body to by-law-making…	is not needed at all.	is needed in certain matters.		
Approval of a higher administrative body to adopt a budget and to manage urban organs…	is not needed.	is needed.		
Issuing building permit…	is in the jurisdiction of the municipal council. (In Fiume, the Municipal Council delegated this authority to the jurisdiction of the Administrative Committee. This right was abolished in Fiume in 1913.)			is in the jurisdiction of the Administrative Board.
Control over the local police…	is in the jurisdiction of the municipal council (In Fiume until 1913).			is in the jurisdiction of state bodies.
Municipal surtax, %	25–500	25	0	
Marketable municipal properties, 1000 gulden	0–150	100	0	
The amount of borrowable loan, 1000 gulden	Variable figures. A few examples: Vienna: 2000 Linz: 100 Klagenfurt, Brno: 50 Graz: 25	The average of total yearly budgetary income from the last three years.	0	

Source: Based on the information of AA, 1850; AA, 1861; AA, 1908; HA, 1870; HA, 1872a; HA, 1872b; HA, 1886a; HA, 1886b; HA, 1901, and the author.

ters, but compared to other Austrian cities, its Municipal Council had a relatively limited or average scope of action.

However, the statutes of the cities had not been modified over time but Fiume's autonomy was torpedoed through state governmental decrees. However, the Hungarian port city could defend its authority for a long time compared to the Hungarian Municipal Towns. A specific governmental decree came into force in Fiume in 1901 that had been enacted in Hungary in 1876. This act empowered the Governor's Council with comprehensive supervision over delegated state powers at the municipal level and stricter oversight of municipal jurisdictions. In 1913, citing the unceasing chaos of the urban administration, the Hungarian government eliminated the special status of the port and later took over the management of the local police (HA, 1916). Meanwhile, Trieste's statute was not significantly modified, allowing it to retain its authority. Compared to Fiume, this was definitely an advantage. However, compared to other Austrian cities, it could be considered disadvantageous, as the jurisdictions of many Austrian cities expanded over time (mainly in financial authorities), and ethnic conflicts were mitigated by electoral reforms.

Conclusions

This research aimed to explore urban governance systems beyond the experience of American cities after the 1970s, focusing on two Central European cases from a historical perspective. The study analyzed the first urban statutes of Trieste and Fiume during the era of the Late Habsburg Empire, revealing that numerous historical, legal-administrative, and socio-economic-political factors shaped their early institutional structures and municipal authorities.

The comparative research showed that these factors significantly influenced both cities' institutional structures and municipal authorities. A crucial *historical factor* was Trieste's and Fiume's special statuses which were maintained for almost 150 years before the Compromise of 1867. Undoubtedly, this historical fact secured the continuation of the special statuses but at the same time, the newly established *legal and administrative factors* complicated the formulation of their governance systems. Trieste got simultaneously rights of a municipality and crownland with reduced autonomy compared to other Austrian cities. In contrast, Fiume, directly submitted to the Hungarian parliament, had unique jurisdictions not shared by other Hungarian municipalities. The study revealed that *socio-economic-political factors* also played a crucial role in formulating the governmental structure of the cities. Both ports, as key sea trading gateways, were significant from the perspectives of Austrian imperialism and Hungarian nationalism. These perspectives, along with socio-economic factors, differently affected the governmental systems of Trieste and Fiume. The ports' initial statutes favoured Italians, and the curial electoral system in Trieste and the lack of virilism in Fiume maintained Italian dominance. However, growing Slovenian and Croatian national movements paired with Austrian and Hungarian political ambitions disrupted local politics and resulted in different solutions from the Viennese and Budapest governments. The status quo was sustained in Trieste, even amid provincial agreements throughout Austria, while Hungarian governments increasingly opposed Croatians and Italians in Fiume and Croatia-Slavonia. Despite Fiume's effective resistance to Budapest's centralization policies, its authority quickly diminished after the turn of the century.

The cases of Trieste and Fiume demonstrated that both the transformation thesis and metagovernance perspectives were applicable not only in combination but also within a historical spectrum. The perspective of metagovernance in this study showed that the legislative and political roles of state actors in urban governance systems were decisive in the cases of Trieste and Fiume. The analytical framework of the transformation thesis also yielded useful results. Several factors indicated that both urban government's and urban governance's characteristics were present in the municipal administration systems of these port cities. Their highly fragmented urban governance scenes, the right to approve state acts regulating their administration, and their participation in national matters through their representatives in the national parliaments resembled the philosophy of urban governance. However, the strict supervision of their municipal matters, especially the narrow financial authority and the gradually reducing overall autonomy of Fiume, pointed to the idea of urban government.

Based on these results, this study aligns with the conclusions of British experiences mentioned in the theoretical section (Andrew, C. and Goldsmith, M. 1998; Goldsmith, M. and Garrand, J. 2000; Pierre, J. 2005). However, this research extends beyond them by including and analyzing the effects of additional dimensions (historical, administrative-legal, and socio-economic-political) on the formation of early urban governance systems in the 19th century. Geographical context proved highly relevant in researching urban governance, as DiGaetano presumed (DiGaetano, A. 2009). Even within a single state formation, geographical location and administrative position were crucial. The comparison of Trieste and Fiume highlighted the importance of rethinking analytical frameworks of urban governance, showing that different historical times combined with different geographical contexts could create unique circumstances for the formation of urban governance systems.

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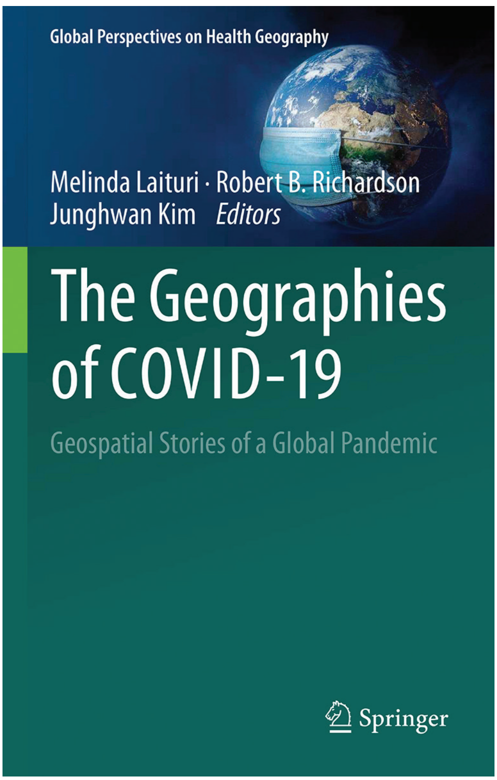
BOOK REVIEW SECTION

Laituri, M., Richardson, R.B. and Kim, J. (eds.): The Geographies of COVID-19: Geospatial Stories of a Global Pandemic. Cham, Springer, 2023. 300 p.

Although the World Health Organization ended the pandemic preparedness regarding COVID-19 diseases in May 2023, the novel coronavirus is still with us, it continues to cause new infections and deaths, even if in smaller numbers than previous variants. We can count on its presence in the coming years as well, but it is unlikely that a new global spread will occur. However, it is a fact that even several years after the outbreak of the pandemic, information and knowledge is coming to light that helps us understand why SARS-CoV-2 coronavirus was able to appear in all countries of the world, and why it was able to cause new and new epidemic waves for more than two years and why it was associated with mass, large-scale deaths. The task of scientific research is to examine recent events from multiple perspectives and using different methods,



analyse the mutual effects, and learn more about the characteristics of the epidemic, which can help in more effective preparation for a similar epidemic situation in the future. One outcome in this learning process is this book, which analyses the relationship between health and place from a global perspective through the geographic features of the pandemic. That is why the current book plays an important role in the literature on place-based approaches to the COVID-19 pandemic and constitutes a basic reading for those interested in geospatial analyses.

The book of *The Geographies of COVID-19: Geospatial Stories of a Global Pandemic* was published by Springer in 2022, edited by Melinda Laituri, Robert B. Richardson, and Junghwan Kim, but a revised edition was out in 2023. Despite the fact that it was published at the last stage of the pandemic, it still provides relevant information about the territorial and geographic aspects of the epidemic nowadays.

The book is part of the 'Global Perspectives on Health Geography' series, the ultimate goal of which is to show the complex ways in which places influence and directly impact human health. The series publishes a comprehensive portfolio of monographs and edited volumes that document the latest research results in the discipline of health geography. This book is a proof of the integration of approaches to examining spatial and place-based aspects of health and health care across different territorial scales from the global to the local. However, this volume also presents a connection between health geography and social science disciplines (e.g. spatial science), and in doing so highlights the importance of spatial thinking.

Although the book as a whole is intended to help the reader discover the complexity of geographies of COVID-19, all authors devote a short preface at the beginning of their chapter for 'storytelling' of personal experiences to make pandemic understandable. These personal stories show how this pandemic could manifest over space and time, but many of them reveal geographic factors and patterns that are examined by geospatial analyses in the chapters of this book. Countless authors, including geographers, have examined the geographies of COVID-19 in recent years, so collecting, analysing, and summarising the essence of their results is not an easy task. The book does not even undertake this, but instead presents case studies at different territorial scales and mainly using quantitative (mathematical and statistical as well as modelling) methods, and ultimately develops a geospatial concept on health inequalities and their geographic formations regarding the novel coronavirus epidemic.

All three book editors come from different fields of environmental science, which guarantees multidisciplinary research on socioeconomic inequalities. Melinda Laituri is a professor of geography focusing on geospatial research and has many research activities on using GIS. Robert B. Richardson is an ecological economist with interests in the study of environment and development, particularly the contribution of ecosystem services to socioeconomic well-being. Junghwan Kim received his PhD in geography and his specialties are e.g. human mobility, travel behaviour, environmental health, and geospatial data science and applications. They invited researchers, lecturers, students, and practitioners from around the world to adopt a geographic focus on presenting and explaining the triggers and consequences of the pandemic across space and time. Their efforts are to be appreciated, but they were partially unsuccessful, because the authors do not cover all the large geographical regions of the world. The coverage of Europe is rather incomplete and Eastern Europe is completely missing from the case studies. Only one author is from South-eastern Europe, from Serbia (Alexandar Valjarević). Most of the authors are Anglo-Americans, but many of the others also represent US universities with their scholarships or as guest lecturers. They make it possible to present in the book some interesting and remote regions and countries during the pandemic, e.g. see Bangladesh, Ecuador, Kenya, Mongolia, New Zealand, Uganda, etc.

Using case studies and examples of geospatial analysis, this book examines several places around the world that have experienced the effects of the pandemic in different ways to discover inequalities and vulnerabilities. These case studies vary across space and time and focus on both the first- and second-order impacts of the COVID-19 pandemic. First-order impacts are generally direct and immediate responses to the pandemic in the short- and medium-terms, and are related to health care and its functioning. They include, for example, tracking the number of infections and deaths, testing, access to hospitals, impacts on essential workers, searching for the origins of the virus and preventive treatments such as vaccines. Second-order impacts might be direct and indirect, but all of them are essentially policy responses of decision-makers to the consequences of the pandemic. These actions, practices, interventions can vary in time, even in the short-, medium-, and long-term, but they primarily reflect on the socioeconomic, environmental, cultural, etc. effects of the pandemic. For instance, in the short-term, different policies are in response to the spread of the virus, in the medium-term, interventions regulate everyday life (access to public services), or in the long-term, actions are addressed to food security. Overall, these effects, responses, and interactions can be excessively diverse spatially, and this book itself demonstrates their complexity using geospatial tools at different territorial scales. This volume provides a synopsis of how geography and geospatial approaches are used to understand the pandemic itself and its multi-dimensional consequences.

The book consists of three major parts, which are fundamentally overviews of the following main topics: Part I Geographies of a Pandemic – A Place-Based Approach; Part II Global Impacts, Local Responses; Part III Lessons Learned and New Horizons. In addition, there is an introductory chapter on the theme of how COVID changed our daily life (Marie Price).

Part I with six chapters provides an overview of the role of geography in the COVID-19 pandemic. Its five chapters mainly show those quantitative methods, such as geospatial tools and technologies, that were applied in measure of the COVID-19 pandemic, but this part is also used to define the first- and the second-order impacts. I would like to highlight three main interesting points among the many valuable and informative results in this part. First, Chapter 4 (Junghwan Kim, Kevin Wang, and Sampath Rapuri) provides a comprehensive review based on 331 papers that have adopted quantitative geospatial approaches and presents three main research topics: 1) investigating geographical disparities in COVID-19 cases and deaths as well as the accessibility to COVID-19-relevant facilities such as testing and vaccination sites; 2) examining various factors that affect COVID-19 cases and deaths and building a model to predict those in the future; 3) other sub-topics include studies that have developed and proposed new algorithms and methods to control the pandemic. Second, mapping has become a privileged part of defining and measuring the first- and the second-order impacts of the pandemic, e.g. there is a map of 72 countries depicting the share of respondents to a high-frequency phone survey that stopped working since the COVID-19 outbreak (Chapter 3 by Robert B. Richardson). Third, it is useful to mention the Cities' COVID Mitigation Mapping (C2M2) programme, led by the US Department of State between summer 2020 and autumn 2021, illustrating the scope of participatory mapping partnerships for second-order impacts of the pandemic, especially in developing regions such as Latin America, Sub-Saharan Africa, and East Asia (Chapter 6 by Laura Cline and Melinda Laituri).

Part II with ten chapters as case studies presents ten places around the world that have experienced the effects of the pandemic in different ways. Each case study demonstrates different geospatial methods, models, and analyses, emphasising the differences and commonalities across space and time where fundamental inequalities exist and which may be the result of the pandemic. These case studies ultimately present a global view of the COVID-19 pandemic from local perspectives through diverse governmental responses. They are suitable to emphasise the vulnerable populations regarding the pandemic that are found throughout the world, e.g. Latine communities or racial/ethnic minorities in US cities, people living in peripheral, informal settlements in Ulaanbaatar (Mongolia), victims of domestic violence in Quito (Ecuador), indigenous groups in Australia, etc. These examples can even be considered good practices that provide lessons for the future, either from the point of view of sustainability or resilience. Among these valuable and useful case studies, I would like to highlight one in Uganda that describes the impact of government policies on the Boda-Boda drivers and its multiple consequences on local society (Chapter 16 by Harriet Kebirungi and Hadijah Mwenyango). Boda-Boda motorists transport passengers and goods with a high physical interface, which creates a conducive environment for spreading COVID-19 in East African countries. This was the main reason why this transport sector was primarily affected by lockdown. The authors of the chapter applied quantitative methods to collect data on the geographical characteristics of Boda-Boda motorists, e.g. using GPS to measure distance between Boda-Boda stages and social services. Secondary data analyses represented the characteristics of the research population, who should be between 25 and 34 years of age, be married, had only primary educational level, and be with 2–4 years of experience in the Boda-Boda transport industry. In addition, most of them bought Boda-Boda motorcycles on loan and were engaged in Boda-Boda as their sole source of income. The study shows that Boda-Boda motorists averagely operated in a distance of between 0–2.291 km and 8.932–11.926 km. The used qualitative methods such as focus groups reported that Boda-Boda motorists lost their jobs and could not provide basic needs to their families. The impact of the COVID-19 lockdown also contributed to food insecurity and domestic violence due to lost daily income. The results of this examination underline that policy reforms and awareness are needed to understand the different forms and interactions of social vulnerability, and there is also a need to plan for protective systems to manage income problems among vulnerable populations (Harriet Kebirungi and Hadijah Mwenyango).

Part III with six chapters explores how the lessons learned from the COVID-19 pandemic set the stage for next steps as the world prepares to adapt to a post-pandemic reality. This part includes examples of mitigation strategies and adaptation pathways that illustrate how they can be used to inform decisions and policies in response to ongoing and evolving challenges. The most important findings of these chapters can be interpreted at various scales ranging from local to national to global and can help to understand the role of geospatial approaches in data-driven decision-making. Here are some examples to help prepare for future outbreaks. For example, Valentina Albanese and Giorgio S. Senesi (Chapter 18) provide an overview of the 'Italian Immuni App', developed as a protocol for citizens who have tested positive for COVID-19 and their contacts, but it considers the protection of personal data and does not allow the identification of patients. In Chapter 21, Maya Mishra describes the framework of 'One Health' based on Earth observations data for predicting and preventing disease incidence in the future, taking an interdisciplinary perspective that recognises the overlapping priorities of human, animal, and environmental health. Ashley Pierce and Amanda Shores (Chapter 22) offer lessons learned from 'RAPID' as Rapid Response Research, which is a response by the US National Science Foundation to COVID-19, reinforcing the need for interdisciplinary research and integration across the diversity of researchers to solve interwoven challenges in times of rapid change and urgent need.

At the end of this book review, I would like to highlight three things that subjectively reflect my opinion about this publication. The book combines masterfully the various theoretical and methodological frameworks of different disciplines and academic backgrounds, but always with a geographic perspective grounded on different scales of COVID-19 analysis. The common goal is to develop a place-based approach that reveals the multidisciplinary context of inequalities and vulnerabilities which exist and may increase in the world in connection with the pandemic (Chapter 2 by Melinda Laituri). In this regard, many relevant results and definite statements can be found in the pages of this book, one of which is here in the interpretation of Xiao Huang and his co-authors (Chapter 8): "Vulnerable populations are less likely to follow the order to stay at home, pointing to the extensive gaps in the effectiveness of social distancing measures between vulnerable populations and others" (Xiao Huang, Siqin Wang, and Xiao Li; p. 90).

All chapters of the book well represent how editors and authors explore the COVID-19 pandemic's effects and consequences from global, regional, and local perspectives, but in addition to all this, they also clearly illustrate how the geospatial approach appears in the support of data-based decision-making. Namely, data-driven decision-making is needed as geospatial analyses and resulting maps navigate in the pandemic and its first- and second-order impacts and determine ways to address future such events. At the same time, they also provide a lesson on how the new tech tools and smart devices that became widespread at the beginning of the 21st century can represent a new alternative for geographical research.

Finally, in addition to my words of appreciation, I should give space to my critical comments as a researcher from Central and Eastern Europe. As I wrote earlier, I miss more European case studies, although it is welcome that the global overview is very broad, covering several large regions of the world. However, it would have been important to present some Eastern European regions or countries, because one of the highest COVID-19 mortality rates was registered here. Moreover, in these countries, the health care inherited from the socialist past faces serious challenges more than 30 years after the regime change. There are marked health inequalities in these societies that have contributed greatly to the high number and rate of COVID-19 cases and deaths. I should also mention that the main findings of the book are relevant to Central and Eastern Europe, however, it would also be important for this region to know how the geospatial approach can be used to measure existing health inequalities and how GIS can be applied in health promotion. For my other critical comment, although the book presents the possible scientific application of geospatial tools, the maps in the book are of medium rather than better quality.

Overall, I recommend this book not only to health geographers, but also to professionals, researchers, university lecturers, and students who are open to a place-based approach in the investigation of the long-term effects of the COVID-19 pandemic, as well as to those who deal with GIS and want to learn more about geographical studies and their possibilities.

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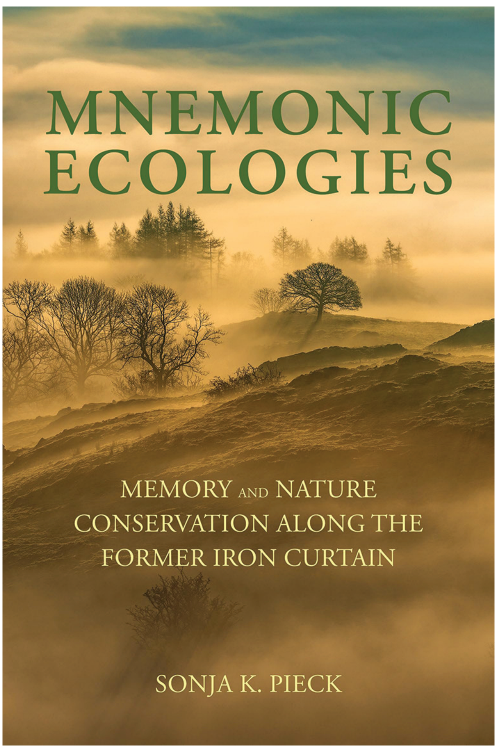
Pieck, S.K.: Mnemonic Ecologies: Memory and Nature Conservation along the Former Iron Curtain. Cambridge, Massachusetts – London, England, The MIT Press, 2023. 280 p.

The question of the entanglement between nature and memory is of crucial importance for post-humanist thought and inclusive humanities in the age of the Anthropocene. While discussions surrounding conservation and ecological restoration are vibrant, the challenge of how to care for ecologically significant spaces marked by historical events is less common and difficult to address. The book *Mnemonic Ecologies: Memory and Nature Conservation Along the Former Iron Curtain* offers a thorough and in-depth reflection on how to sustain ecosystems while respecting the need to memorialize difficult pasts associated with specific, historically shaped spaces.

The author of the book, Sonja K. Pieck, is a human geographer of German origin, who currently works at Bates College (USA). She earned her Ph.D. from Clark University (USA). Her research focuses primarily on environmental protection and its institutional shaping, ecosystem governance, the mutual influence of nature and history, and the meanings attributed to ecological entities by people in different cultural contexts.



Above mentioned fields of her research are all addressed in *Mnemonic Ecologies*. Pieck's book comprises six chapters, along with an introduction and a conclusion. The first chapter offers a theoretical exploration of the concept of mnemonic ecologies, while the second focuses on the historical development of the Green Belt project in Germany. The subsequent three chapters address various aspects related to the existence of the Green Belt, including commemoration, politics, environmental management, and artistic initiatives. The sixth chapter provides an overview of diverse locations worldwide where the concept of mnemonic ecologies, as developed in Germany, could serve as a valuable source of inspiration.

The book explores the remarkable Green Belt project in Germany, a space that emerged from the division of the country during the Cold War. The Green Belt consists of the former border that not only separated East and West Germany but also symbolized the divide between the opposing sides of the Cold War, the so-called Iron Curtain, which, as Churchill famously stated in his Fulton speech, had "descended across the Continent." The Green Belt project stretches from Thuringia to the Baltic Sea, covering an area of 17,712 hectares and extending nearly 1400 kilometres. Following the collapse of the Soviet bloc and the reunification of Germany, this former border was gradually dismantled, leaving behind material remnants that have since fallen into decay. It was soon observed that within this artificially created space, many species of plants and animals, particularly birds, that had become rare elsewhere, were thriving. The former border had provided them with a safe refuge. This observation led to the recognition of the need to manage this "no man's land," sparking a long-lasting debate among conservationist and environmentalist, about how to sustain this socioecological hybrid. However, the discussion could not be limited to the natural features of the belt. It also had to address the social dimension of the border's difficult history. This included the trauma of the displacement of people who lived in this area before the border was established, as entire villages were destroyed to create the militarized zone. There was also the trauma associated with the attempts to cross the border, which resulted in the deaths of hundreds of people trying to escape the German Democratic Republic. Therefore, the uniqueness of this space lies not only in its distinctive ecology but also in its historical significance and the ways in which the past of the former border is remembered.

In the book, Pieck raises crucial questions about how to integrate ecological perspectives with historical ones. The first chapter focuses on conceptualizing mnemonic ecologies, a term used to describe the "complex and mutual entanglements of emerging ecosystems and historical memory" (p. 9). This refers to a layered landscape shaped both by human activity and the agency of non-humans, which find ways to interact with artificially created spaces that have passed the point of no return to their former state. Such spaces are referred to as *novel ecosystems*. The landscape layers are shaped by an ongoing, emotional process of ascribing meanings to places and the ways they are remembered. The book effectively demonstrates that it is impossible to focus solely on the ecological aspects of such spaces. As Pieck convincingly argues, "ecologies have pasts, and pasts are crafted through ecologies" (p. 22). In this theoretical section of the book, Pieck engages with key scholars from memory studies, including Jan and Aleida Assmann, Maurice Halbwach, and Simon Schama. Given Pieck's attention to sensory and bodily engagement in the process of memorialization, it might have been valuable to include Paul Connerton's *How Societies Remember* (Cambridge, 1989), which naturally comes to mind when reading this work. In addition to addressing human memory, Pieck poses thought-provoking questions about the capacity of non-human entities to remember, and how their memory can shape landscapes. The non-anthropocentric perspective introduced through these questions as well as the empathy demonstrated towards human beings and inclusion of moral considerations regarding human memory, enriches the book, rendering it both poignant and profoundly compelling.

The subsequent chapters of the book explore the history of the German Cold War border and its enduring effects. A significant part of it focuses on the ecological initiatives spearheaded by scientists and activists from both sides of the former border in their efforts to manage the diverse ecosystems of the Green Belt. The main figure that is responsible for lunching the Green Belt Project is BUND – the German Federation for the Environment and Nature Conservation (*Bund für Umwelt und Naturschutz Deutschland*). Pieck offers a detailed analysis of various approaches to ecological restoration, ranging from "passive management" (no intervention) to more active interventions aimed at countering natural processes that threaten habitats that developed as a result of the Cold War division. Additionally, she examines restoration strategies that seek to reestablish the original structure of the ecosystem, with the ultimate goal of creating self-sustaining environments within the Green Belt. Pieck highlights how these differing approaches are not only a matter of ecological debate but also deeply embedded in political discourse, shaped by both historical perceptions of the landscape and the present-day needs of communities living near the belt. With great sensitivity, she addresses the tensions between different advocacy groups, each promoting distinct visions for the future of the Green Belt.

A particularly compelling aspect of these discussions concerns the concept of *Heimat* that is discussed in the third chapter of the book. Here, the idealization of *Heimat* can be traced back to the romantic period of the 18th and 19th centuries, when the notion of homeland intertwined cultural heritage with a specific landscape, forming an essential element of identity for those inhabiting the area. As Pieck aptly observes, "the Green Belt today is a composite of old and new, a product of backward-looking nostalgia and, more recently, a range of future-oriented, scientific concerns that crystallized in the postwar decades" (p. 72). However, the idea of *Heimat* also carries the burden of its more ambiguous 20th-century appropriations, particularly in its nationalistic and Nazi connotations. Nonetheless, as Pieck explains, *Heimat* remains a deeply emotional and unavoidable element in the Green Belt's restoration process, influencing the perspectives of individuals engaged in its outcome.

Thus, the vision for conservation, as articulated by representatives of the natural sciences, eco-activists, and regional authorities, is inextricably linked to subjective interpretations of the past, memory, and a deep attachment to place. Pieck persuasively argues that ecological projects cannot focus solely on environmental factors. They must also account for human memories, emotional ties to the landscape, and the complicated, often traumatic, history of the region. This nuanced perspective is a testament to the author's sensitivity in handling the multifaceted subject matter of this remarkable book.

In the fourth chapter of the book, Pieck delves into various projects that engage with the historical legacy of the Green Belt. In these initiatives, nature becomes a medium for commemorating the past, what Pieck refers to as "mnemonic ecological projects." Here, the landscape is actively shaped by human actions, such as the creation of art installations or memorials, but it is also influenced by non-human agents that co-construct this complex space. Pieck discusses notable examples – landscape art projects, such as the *Three Cross of Ifta*, *The West-East Gate*, Mario Goldstein's book *Green Belt Adventure: 100 Days by Foot along the Former German-German Border*, and the BUND's website, *Monumental*. In these cases, nature, memory, and history are interwoven, helping people reconcile with a difficult past. Nature, in this context, serves as both a historical marker and a healing force. Its specific ecology within the Green Belt gently reminds us of the region's layered history through acts of commemoration and ecological distinctiveness from the surrounding areas.

A particularly compelling section of this chapter examines the role of power within conservation discourse, shedding light on *who* shapes the memory of this space and *how*. The act of ecological conservation is inexorably with the commemoration of partitioned Germany's troubled history. As Pieck observes, "*natu-*

ral heritage becomes *national* heritage" (p. 118, emphasis in original). Yet, this national identity project carries two ambiguous aspects. On one hand, it recalls the traumatic past, which is essential to identity building processes. On the other, it underscores the lingering divide between Western and Eastern Germans. Two German identities not always seamlessly unified as ongoing debates about what it means to be "Ossi" and "Wessi" in Germany show. However, as Pieck perfectly showed, ignoring the history is not the solution, because the past is present there anyway. People remember and inevitably add the historical values to this uncanny ecological phenomenon.

The fifth chapter of the book offers a powerful exploration of how non-human actors shape the Green Belt and how their forms of memory influence its ecology. This insightful section challenges the anthropocentric perspective, exposing the limits of human language, which often overlooks the non-human impact of the tragedy brought about by the border's creation. It also reveals that conventional understanding of such notions like "cultural landscape" are no longer enough in describing the processes occurring in such a unique space. Pieck highlights that "[e]cosystems both perform memory of human beings and have their own forms of memory" (p.122), viewing the former border as an act of violence that had impact on non-human actors, exposing them to suffering and forcing them to adapt to a new reality. The ecosystem still bears the presence of chemicals used to create the border, the destruction of certain species, and the deadly remnants of fortifications. However, some species use the opportunity to develop in this environment, embodying what Pieck terms an "ecological legacy" that gives rise to *novel ecosystems*. But its condition today is still often sustained *against* natural succession, like in historical region of Eichsfeld (parts of Lower Saxony and Thuringia) part of the Green Belt.

The significant part of the chapter is devoted to varied managements across The Green Belt ecosystems. In some parts, like *Eichsfeld*, the ecosystem's current state is sustained intentionally to support both needs of local people, and species that emerged because of the violent history of the border. In addition, the example of Rodach Valley, where heck cattle – a rebreed of the extinct aurochs – along with sheep and goats, show how they help to maintain open land and control natural processes. Another example demonstrated different approach. Along the Elbe river, "rewilding" efforts aim to revive an ancient ecosystem. All these "sensitive spaces," as Pieck calls them, are carefully designed by conservationists, yet these designs are not always controllable or predictable. Nonetheless it operates in the mnemonic dimension and needs to take into account the political, economic, and social contexts as well.

The final chapter broadens this framework to other parts of the world where the concept of *mnemonic ecologies* might apply, such as the Korean Demilitarized Zone, with additional examples like ecological restoration cases in Colombia and Cambodia. The author also examines the European Green Belt initiative, which was launched in 2004 with the aim of establishing a similar space along the former boundary between communist and non-communist states, stretching from the Balkans to Fennoscandia. While the concept of re-establishing the Green Belt within the geographical and historical context of the Iron Curtain holds potential for partial realization, other examples in this chapter should rather be treated as sources of inspiration. Examining conflicted places with traumatic histories from the perspective of the Green Belt project, may be however – as Pieck argues – inspiring for different parts of the world.

Pieck's book is a remarkable demonstration of how profound analysis of a detailed case study can lead to impactful theoretical contributions. Her thorough study of the Green Belt project leads to the development of the valuable concept of mnemonic ecologies, likely to resonate in the *milieu* of scholars interested in the intersection of nature and memory. By addressing remembrance, ethics, and sensitivity to both human and non-human perspectives, this book becomes an inspiring and thought-provoking reading.

Małgorzata Praczyk[1]

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