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Heatwave vulnerability and climate policy assessment in Central Europe: A comparative study of Hungarian and Slovak cities

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ABSTRACT

The occurring and projected changes in climate patterns and associated demographic, socio-economic, and environmental factors make Central European cities vulnerable to heatwaves. However, urban areas in the Carpathian Basin, located just a few hundred kilometers apart, exhibit diverse geographical and microclimatic conditions contributing to distinct local-specific features. This paper aims to analyze the vulnerability of Hungarian county seats and Slovak regional seats to heatwaves by integrating statistical indicators, remote-sensing data, and qualitative information on urban climate strategies. By comparing less-studied urban areas, this paper fills a gap in the current literature and provides an easily adaptable assessment methodology incorporating quantitative and qualitative methods, which were rarely combined in previous research. The results highlight significant differences in sensitivity and adaptive capacity factors among the selected cities while also revealing country-specific aspects of policy-making strengths and weaknesses.

1. Introduction

Climate change presents a growing challenge for urban areas (IPCC, 2021). Changing precipitation patterns and intensifying extreme heat events increase the vulnerability of cities, emphasizing the need for well-planned and effective responses (Elmqvist et al., 2021). The rapidly changing climate can have significant negative impacts on overall well-being, such as devastating thermal discomfort (He et al., 2021), increased mortality and morbidity rates (Imran et al., 2019; López-Bueno et al., 2021), and reduced effectiveness of urban green spaces in mitigating heat stress (Marando et al., 2019). To address the adverse effects of climate change on urban areas, it is crucial to have adequate adaptation responses from all stakeholders (Heinzlef et al., 2020; Pasquier et al., 2020). Identifying underlying factors plays a pivotal role in extreme weather events. It is understood that local socio-economic, environmental, and microclimatic features can inherently determine (Otto et al., 2021; Wu et al., 2022; Zhou et al., 2022; Ziervogel et al., 2022) or even predict vulnerability patterns (Eini et al., 2020; Kafy et al., 2022; Katal et al., 2023; Shi et al., 2021). Assessing these essential factors can deepen local understanding of vulnerabilities, contributing to the identification of key areas for strengthening resilience (Sera et al., 2019). This requires a quantitative assessment of vulnerability issues based on rigorous and replicable

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methodologies (Diaz-Sarachaga and Jato-Espino, 2020; Zebisch et al., 2021) and effective plans that appropriately address the most vulnerable social groups and economic sectors (Reckien et al., 2023). Considering the magnitude of occurring and projected changes (IPCC, 2022), intensifying heatwaves are the most common challenges faced by cities worldwide (Adnan et al., 2022; Marcotullio et al., 2021; Patel et al., 2022; Shreevastava et al., 2021; Wei et al., 2022), which establishes the relevance of a separate assessment of heatwave vulnerability (Shi et al., 2021; Macnee and Tokai, 2016; Raja et al., 2021; Voelkel et al., 2018). Generally, vulnerability analyses gained significant attention from researchers in the last decade regardless of the geographical location of the selected cities (Bai et al., 2016; Bhattacharjee et al., 2019; Cheng et al., 2019; Macnee and Tokai, 2016; Raja et al., 2021; Voelkel et al., 2018). In recent years, there has been also a growing recognition of the importance of qualitative policy assessments comparing the effectiveness of urban climate adaptation or mitigation plans both within countries (Kern et al., 2023; Pietrapertosa et al., 2019) and internationally (Aguiar et al., 2018; Hunter et al., 2020; Olazabal and De Gopegui, 2021; Olazabal et al., 2019; Reckien et al., 2018, 2019; Salvia et al., 2020).

Despite the growing interest and the associated high impacts, there are still some less studied areas in connection to urban climate and heatwave research. The literature on vulnerability analysis and assessing climate strategies are relatively separated from each other (Zhou et al., 2022). Quantitative studies that address urban heatwave vulnerability devoid of any qualitative considerations, no matter whether they focus on cross-country comparisons (Leal Filho et al., 2021; Sera et al., 2019; Wu et al., 2022; Bokwa et al., 2019; Gál et al., 2021), or lower scales (Cheval et al., 2023; de Schrijver et al., 2023; Kamenská and Smatanová, 2022; Räsänen et al., 2019; Reischl et al., 2016; Wolf and McGregor, 2013). Cross-country and even EU-level comparisons of urban adaptation strategies are more prevalent (Aguiar et al., 2018; Hunter et al., 2020; Olazabal and De Gopegui, 2021; Reckien et al., 2018, 2019; Salvia et al., 2020) but without integrating the qualitative strategy assessments with quantitative data. Therefore, combining vulnerability (sensitivity and adaptive capacity) data with municipal responses (strategies and measures) is a crucial contribution to the literature. In addition, urban areas in Central-Eastern Europe have been less studied compared to their counterparts in Western Europe (Aguiar et al., 2018; Otto et al., 2021). This implies a territorial gap as well, as no comparative assessments of cities in Hungary and Slovakia have focused specifically on climate change-related issues.

Our paper focuses on selected Hungarian and Slovak cities - situated in the Carpathian Basin - from a heatwave vulnerability perspective. According to the output of regional climate models and related studies (Negm and Zeleňáková, 2019; Simon et al., 2023; Torma and Kis, 2022), increasing average temperatures and intensifying heatwaves are projected, along with significant changes in precipitation patterns over seasons. These changes make Hungarian and Slovak cities more uncomfortable in terms of thermal comfort (Ács et al., 2021) and more vulnerable to heatwave patterns (Bokwa et al., 2019; Gál et al., 2021; Kamenská and Smatanová, 2022). Although the regional climate models identified interregional differences regarding the magnitude of the projected changes, these values show the same directions without considerable variations in the raw data. Since Central European cities have and will have

Table 1
List of the selected cities.

Country	Region/county	Regional/county seat	Region/county seat's population (2021)	Region/county seat's area [km^2]
Slovakia	Banská Bystrica	**Banská Bystrica**	76,018	103,4
	Bratislava	**Bratislava**	475,503	367,6
	Košice	**Košice**	229,040	243,7
	Nitra	**Nitra**	78,489	100,5
	Prešov	**Prešov**	84,824	70,4
	Trenčín	**Trenčín**	54,740	82
	Trnava	**Trnava**	63,803	71,5
	Žilina	**Žilina**	82,656	80
Hungary	Békés	**Békéscsaba**	58,002	193,9
	Pest	**Budapest**	1,723,836	525,1
	Hajdú-Bihar	**Debrecen**	200,974	461,7
	Heves	**Eger**	51,168	92,2
	Győr-Moson-Sopron	**Győr**	132,735	174,6
	Somogy	**Kaposvár**	59,777	113,6
	Bács-Kiskun	**Kecskemét**	109,651	322,6
	Borsod-Abaúj-Zemplén	**Miskolc**	150,695	236,7
	Szabolcs-Szatmár-Bereg	**Nyíregyháza**	116,554	274,5
	Baranya	**Pécs**	138,420	162,8
	Nógrád	**Salgótarján**	32,304	93
	Csongrád-Csanád	**Szeged**	159,074	281
	Fejér	**Székesfehérvár**	95,545	170,9
	Tolna	**Szekszárd**	30,963	96,3
	Jász-Nagykun-Szolnok	**Szolnok**	69,725	187,2
	Vas	**Szombathely**	78,324	98,7
	Komárom-Esztergom	**Tatabánya**	65,145	91,4
	Veszprém	**Veszprém**	58,153	126,9
	Zala	**Zalaegerszeg**	55,470	102,5

Source: DATAcube, TeIR.
Note: To improve the readability of this study, we use indexed abbreviations ^{S} for Slovakia and ^{H} for Hungary when mentioning individual cities without further explanation.

significant challenges regarding climate change-induced issues, they should undergo vulnerability assessments. Several Hungarian cities have been the focus of sectoral or regional-level vulnerability assessments (Bede-Fazekas et al., 2017; Biró and Szalmáné Csete, 2020; Csete and Szécsi, 2015; Uzzoli et al., 2018). Moreover, there have been studies on heatwave-related analyses (Breuer et al., 2017; Buzási, 2022; Göndöcs et al., 2018), land surface temperature-based assessments (Dian et al., 2019; Henits et al., 2017; Unger et al., 2020), and climate concerns (Kiss et al., 2022). In comparison, a smaller number of Slovak urban areas have been studied. Generally, the most often targeted cities are Bratislava and Trnava (Belčáková et al., 2019; Feranec et al., 2019; Holec et al., 2020), although Hudec et al. (2017) analyzed a more comprehensive range of Slovak cities in their study. In the case of measurements made using the MUKLIMO_3 model, a temperature difference of up to 4 °C was recorded in Bratislava during the summer heat in 2018, in Trnava 2.5 °C and in the case of Žilina 1.5 °C compared to the countryside of these cities (Kopecká et al., 2021).

Our paper intends to contribute to the existing literature using an integrated methodology to conduct comprehensive research on a less-studied region from a thermal resilience perspective. The objective is to evaluate the vulnerability to heatwaves in Central-Eastern Europe, focusing on Hungarian and Slovak cities. Vulnerability, as we understand it, encompasses sensitivity (level of potential harm) and adaptive capacity (ability to cope with or adjust to the impacts) and refers to the tendency to be negatively affected (Bhattacharjee et al., 2019; IPCC, 2022). Like many scholars, we regard resilience as a concept that has a more positive connotation and is in contrast to the more negatively framed vulnerability (Lin et al., 2017). This research employs qualitative and quantitative approaches to examine vulnerabilities and climate adaptation strategies. The primary focus is on merging existing methods of vulnerability analysis and strategy assessment to encompass a larger number of cities. Our goal is to identify geographical patterns and examine the differences and heterogeneities. Ultimately, this research seeks to answer whether cities with high vulnerability have better strategies to prepare for and reduce the effects of future heatwaves.

1.1. Study area

Our study area contains 27 cities from Slovakia and Hungary (see below Table 1 and Fig. 2). Eight cities from Slovakia serve as the centers of the Slovak regional self-government units (regions). We refer to them as regional seats („krajské mesto“). They account for 21% of the country's population (2021). The remaining nineteen Hungarian cities are county seats (“vármegyeszékhely”). They are also the centers of regional administrative units (counties), and their urban population share 34% of the country's population (2021). In our study area, the two capitals, Bratislava and Budapest, are the most populous cities.

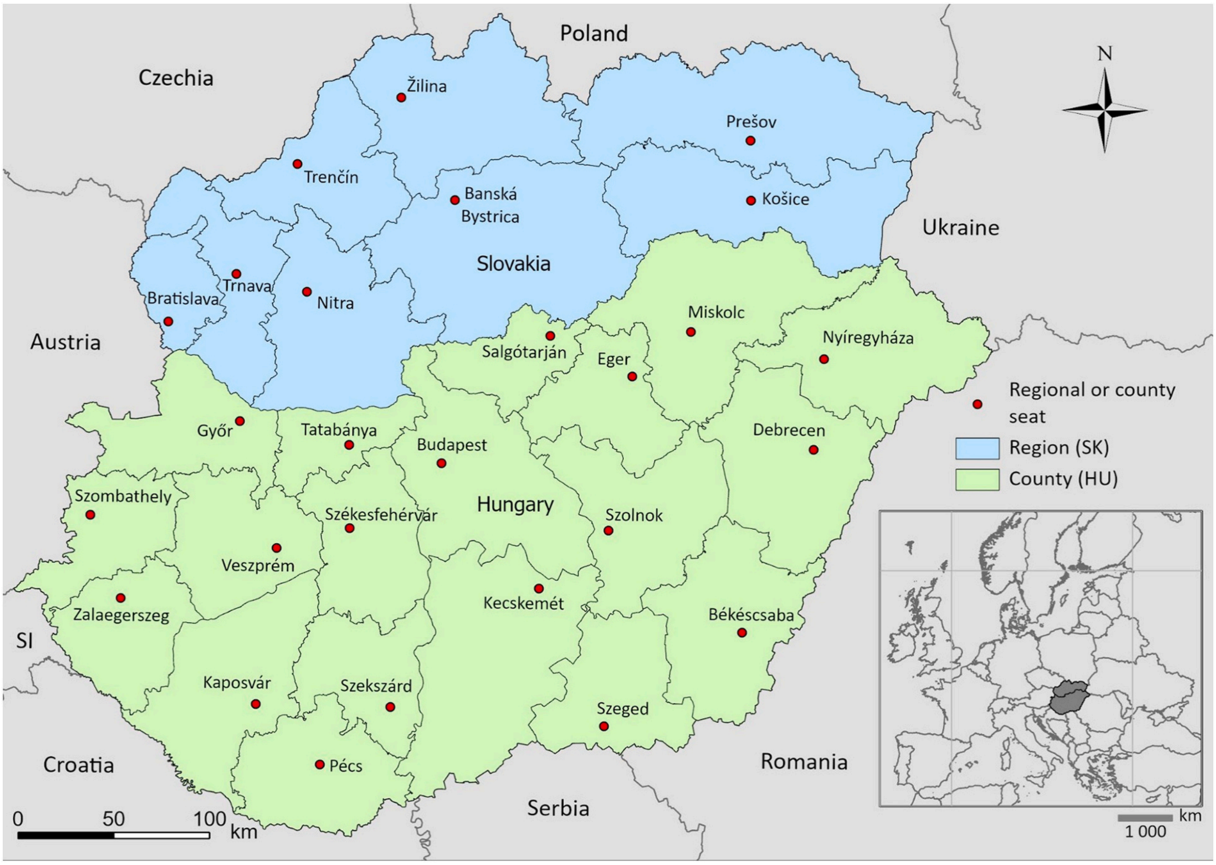

Fig. 1. Study area.

Although our study focuses on two neighboring countries, the region encompasses samples with different geographical characteristics. For instance, the area includes both regional seats in mountain valleys (e. g. Banská Bystrica[S], Žilina[S]) as well as county seats situated on plains, such as Győr[H], Kecskemét[H] or Szolnok[H]. It is worth noting that some Hungarian cities (Szeged and Pécs) already exhibit Mediterranean-like climate characteristics due to climate change (Kántor et al., 2018; Molnár et al., 2020; Unger, 1999).

2. Materials and methods

The applied methodology encompasses both quantitative and qualitative assessments, as illustrated in Fig. 1. Following the study's framework, the initial stage consists of defining a comprehensive set of indicators aimed at various aspects of heatwave vulnerability. Simultaneously, it entails identifying the most relevant policy topics for assessing urban climate strategies. The quantitative analysis adopts two methodological approaches. Fuzzy logic is used to define the overlapping and seamless categorization of vulnerability scores. Consequently, average vulnerability scores are computed to depict city clusters with similar vulnerability. The qualitative assessment is designed to unveil policy preparedness by focusing on risk evaluation and the measures proposed in urban climate strategies. It results in calculating final policy scores by applying a thematic questionnaire to these strategic documents. In the last step of our study, results from both methodical approaches (average vulnerability scores and final policy scores) are synthesized to culminate in a classification of analyzed cities.

2.1. Quantitative analysis: data collecting methods and selected indicators

From a methodological perspective, our quantitative research aims to categorize the selected cities based on their levels of resilience or vulnerability. We began this part by reviewing available literature on heatwave vulnerability assessments and collecting a group of potential indicators. The initial set consisted of 24 sensitivity and 19 adaptive capacity indicators. Subsequently, we explored the availability of each indicator in Slovak and Hungarian statistical and other sources, searching for common ones. Following the removal of duplicate indicators, it became evident that the scarcity of comparable local data between Slovakia and Hungary poses a significant limitation to our study.

We aspired to include more indicators into our research, such as education levels below high school, building renovation rates, and minority ethnic group proportions, which are frequently present in heatwave vulnerability assessments (Eghdami et al., 2023; Hansen et al., 2013; Otto et al., 2017; Pajek and Košir, 2021; Szagri and Szalay, 2022). However, these data are only accessible for Slovak cities. In contrast, Hungarian city-scale data on average annual income, the prevalence of cardiovascular and respiratory ailments, and disabled population percentages, employed in other heatwave vulnerability assessments (Arsad et al., 2022; Buzási, 2022; Inostroza et al., 2016; Johnson et al., 2012; Salvador et al., 2023), are obtainable but unavailable for Slovak cities.

The final set consists of six sensitivity and five adaptive capacity indicators for heat-related climate change impacts (see Tables 2 and 3). They comprise demographic, socio-economic, health, and remote sensing data. Our sources for the first three groups of data, including S1, S2, S3, S4, S6, A1, and A2 indicators, were DATAcube - Database of Statistical Office of the Slovak Republic (https://datacube.statistics.sk/), and TeIR - National Spatial Development and Spatial Planning Information System of Hungary (https://www.oeny.hu/oeny/teir/#/). The remote sensing data for S5, A3, and A4 indicators were collected from the Copernicus Land Monitoring Service. Tables 1 and 2 in the Supplementary summarize the values of each indicator, along with their sources, data source year, and measurement units.

In this section, we discuss indicators that acquired an individual method to be collected. For example, we used the software ArcGIS Pro from ESRI to compile all remote sensing data for three surface indicators. Imperviousness density (S5) and available green and blue areas (A3) are used as static indicators, while tree cover density (A4) is calculated as a percentage change between 2012 and 2018.

The indicator for available green and blue areas required a customized methodological approach. It incorporates all relevant green and blue Corine Land Cover categories, e.g. green urban areas, broad-leaved forests, mixed forests, water courses, and water bodies. At the same time, it excludes agricultural categories like non-irrigated arable land and vineyards due to their negligible cooling effect (Wickham et al., 2012). To determine the value of the A3 indicator, the number of urban populations was divided by the total area of green and blue spaces.

In response to the absence of statistical data on swimming pools in Slovak and Hungarian cities, we devised a systematic data

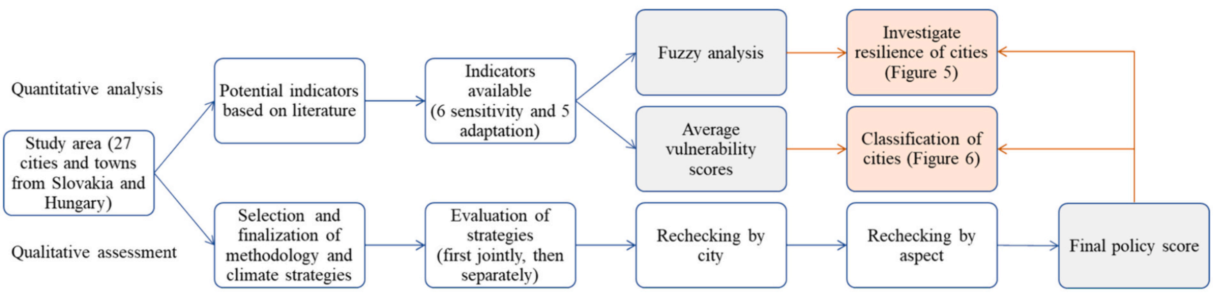

Fig. 2. Methodological framework.

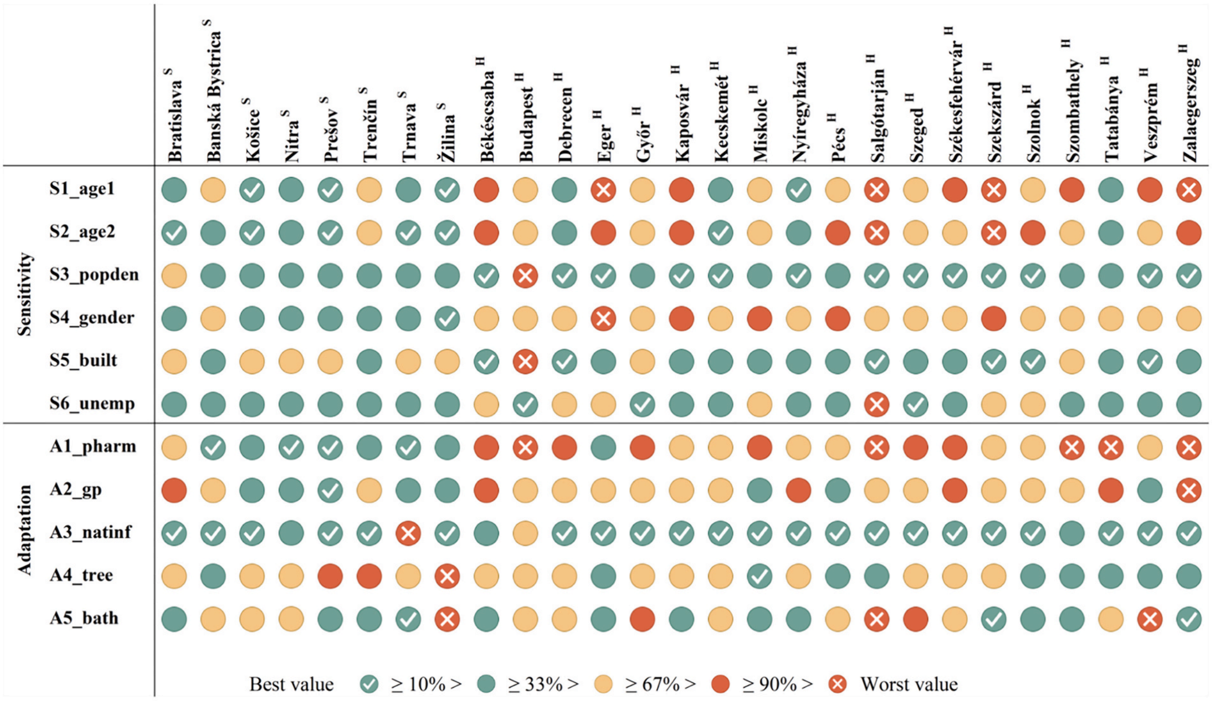

Fig. 3. Comparative results of sensitivity and adaptive capacity indicators in selected Slovak and Hungarian cities[3].
Notes:
[3] For instance, the green point in the first column and first row means that the value of S1_age_1 sensitivity indicator (Ratio of people with age 65 + and 0–2) for Bratislava[S] is in the best third, but not in the top 10% of the values among the 27 analyzed cities.

collection method. The first step comprised deliberate consideration of which types of swimming pools we should gather. From the perspective of heatwave mitigation and urban resilience, we conclude that counting every open-air and public swimming pool is the optimal choice. The data collection occurred mostly via Google Maps and municipal websites. Since local business owners add their businesses to Google Maps to help potential visitors find their precise addresses and opening hours, our search method involved looking for swimming pools listed as local businesses in our selected cities. To enhance accuracy, we verified our data using travel-oriented websites, such as www.travelguide.sk and www.szallas.hu. Finally, by using the number of swimming pools per capita of urban population, we executed a rigorous assessment of their availability in our selected cities.

2.2. Quantitative analysis: evaluation of heatwave vulnerability

In our quantitative analysis, we evaluated the heatwave vulnerability of Hungarian and Slovak cities using an averaging method and a more intricate fuzzy methodology. Mamdani's fuzzy methodology(Mamdani and Assilian, 1975) enabled us to incorporate our individual criteria system alongside the objectively calculated averages. This approach allows a more stringent evaluation of a city's vulnerability to heatwaves, based on specific sensitivity and adaptive capacity values. A comprehensive overview of the fuzzy methodology and a schematic representation of the process are available in the supplementary materials (see Fig. 1. in Supplementary (MathWorks, 2023)). We generated sixteen rules from the various input combinations, subsequently determining the corresponding possible outputs with the maximum number of 5 categories (see Table 5. in Supplementary). The aggregation method compresses the consequent set of rules to create a single fuzzy set for which we applied the maximum aggregator operator. The next step involved defuzzification to find a crisp value that accurately represents a fuzzy set (Tóth-Laufer, 2016), whereby we used the centroid method.

2.3. Qualitative assessment: content analysis of urban climate strategies

According to Bowen (2009), document analysis is a systematic procedure to examine or evaluate documents. It involves skimming (superficial examination), reading (thorough examination), and interpretation of the collected information. The entire process includes investigating, selecting, assessing, and synthesizing the data from the documents. One of its primary functions is to enhance the knowledge base of the examined issue by obtaining information from the assessed documents. To achieve this, we applied content analysis to local climate change plans. Content analysis is a frequently used method (Baynham and Stevens, 2014; Li and Song, 2016; Lyles et al., 2018; Woodruff and Stults, 2016) to assess the rhetorical aspect of urban climate change adaptation.

Considering our research aims, heat-health plans would also be beneficial to assess. Some municipalities are already providing these documents as recommended by the WHO (Matthies et al., 2008). Nevertheless, their distribution varies across countries

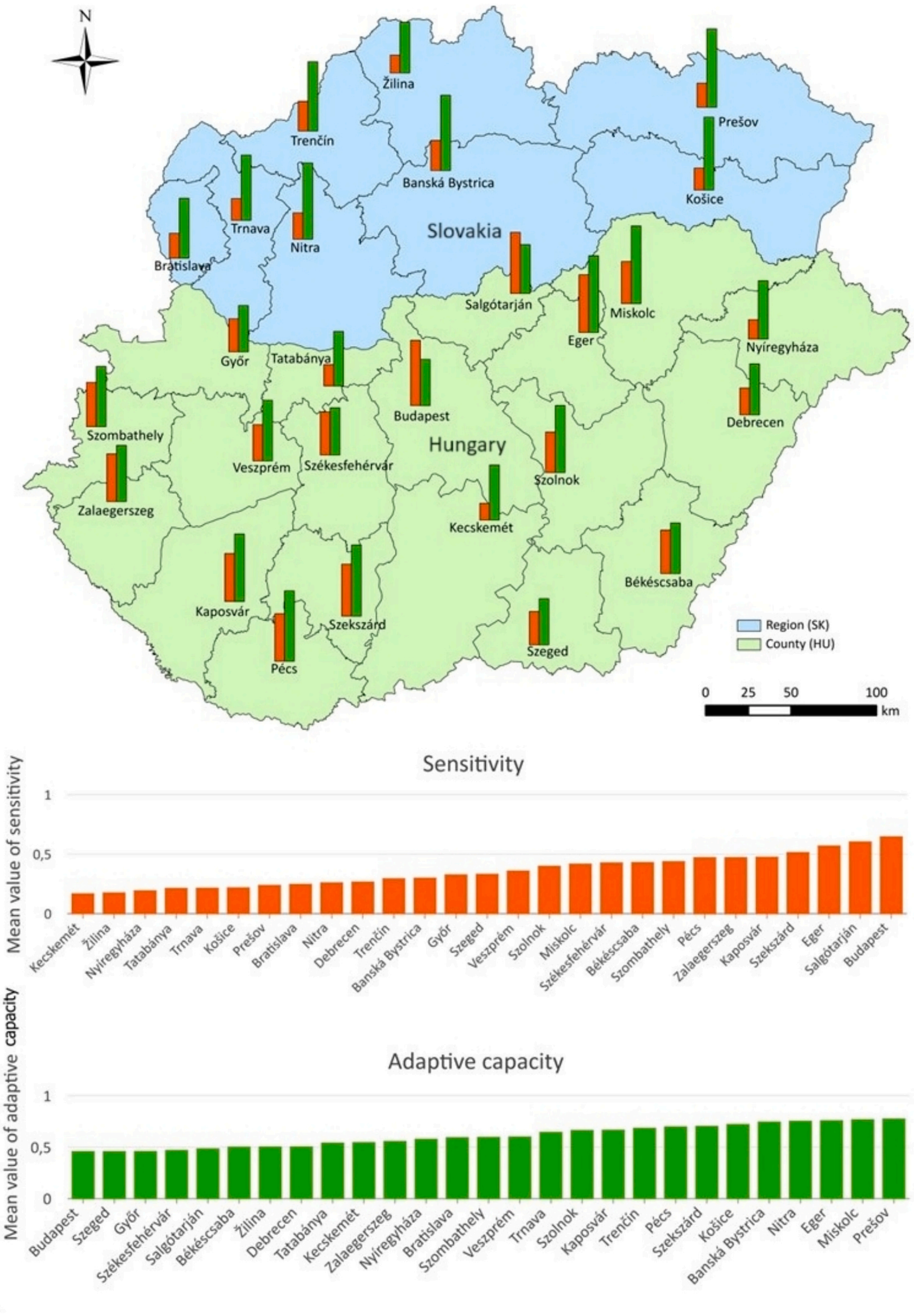

Fig. 4. Heatwave vulnerability (sensitivity and adaptive capacity) of selected Slovak and Hungarian cities.

(Kotharkar and Ghosh, 2022). Currently, there are no municipal heat action plans in Slovakia, while in Hungary, only a few exist, which rely on short-term measures such as heatwave alarm procedures. Consequently, climate strategies offer the most comprehensive information on heatwave adaptation in our study area.

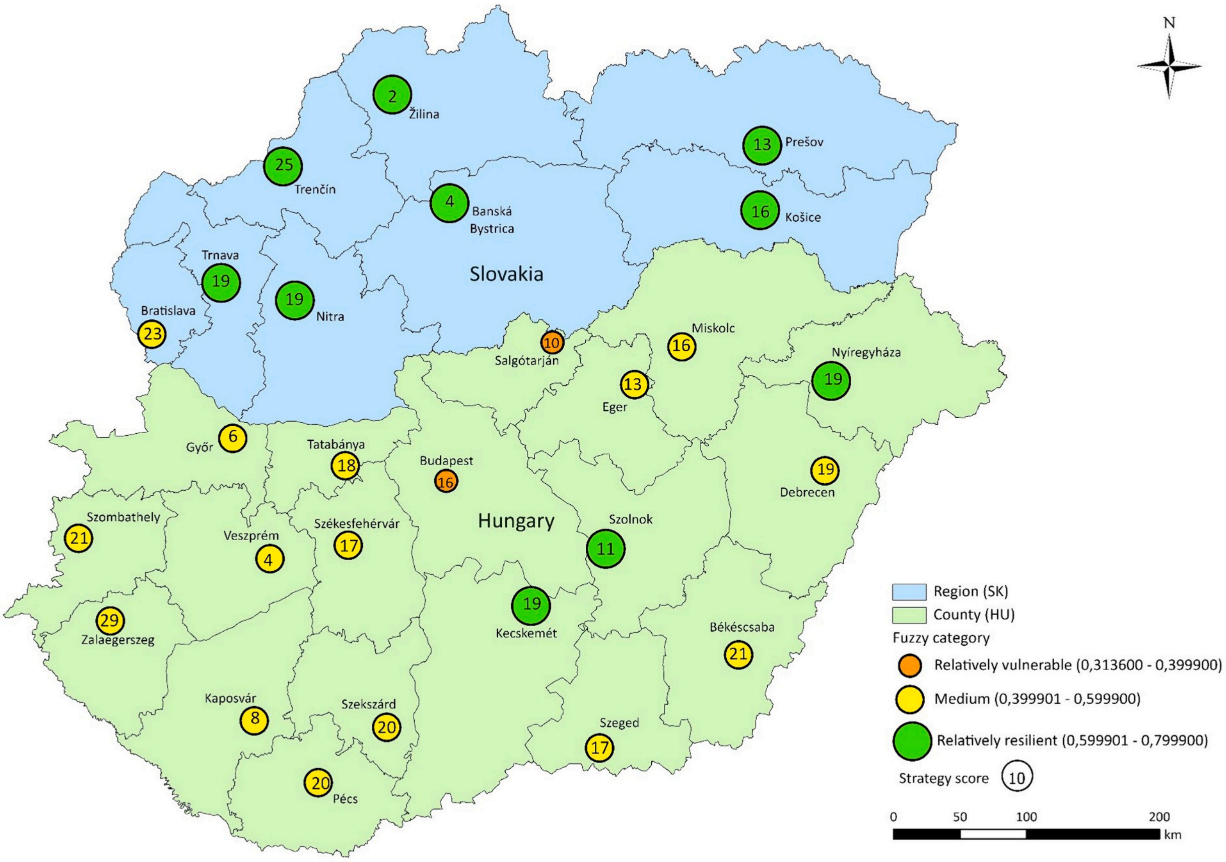

Fig. 5. Fuzzy categories and climate strategy scores of selected Slovak and Hungarian cities.

The majority of climate strategies were gathered from municipal websites. Table 7 in the Supplementary provides their entire list. Only one city, Žilina^{S}, lacked a climate strategy at the time of writing this article. In its case, we assessed the Strategic Development Plan of Žilina until 2025 as a substitute. In addition, we encountered difficulties obtaining the Climate Action Plan for Košice^{S}, as the document was inaccessible to us. We could only assess their adaptation plan.

During the development of our questionnaire (see the following Table 4), our approach was influenced by three research papers (Buzási et al., 2021; Kalbarczyk and Kalbarczyk, 2022; Saha and Paterson, 2008). The evaluation framework, based on the work of Buzási et al. (2021), incorporates thematic questions that encompass general information and specific measures proposed in climate change plans. We adopted their scoring system with minor modifications (see Table 5).

Climate action, like sustainability efforts (Saha and Paterson, 2008), encompasses a variety of initiatives. To fulfill our aspirations regarding heat-related questions, we customized the categorization of adaptation measures in our questionnaire in relation to the work of Kalbarczyk and Kalbarczyk (2022). Overall, our questionnaire comprises three general questions and eight questions focused on specific measures proposed by cities in their climate adaptation plans. The highest achievable score is 30.

The process of policy assessment was divided into four stages. In the first stage, the authors (all fluent in Hungarian) assessed three strategies to ensure the identical application of the scoring system. Subsequently, consultations were conducted in cases of uncertainties. In the second phase, the strategies were evaluated individually by the researchers. This step was required because only one author is fluent in Slovak and could assess the Slovak strategies. Finally, to ensure the consistency of our policy assessment, we compared our climate strategies and cross-checked their scores question by question.

3. Results

The study aims to evaluate heatwave vulnerability in two Central European countries by assessing the preparedness of their county and regional seats concerning their resilience. In this chapter, we first look at the sensitivity and adaptive capacity of the analyzed cities (see Figs. 3 and 4; for more details, see the Supplementary material). Then, we present our findings on heatwave vulnerability resulting in the categorization of cities by the fuzzy method. Following that, we describe the results of the strategy assessment (see Fig. 5). Lastly, we demonstrate our synthesis and classify the analyzed cities according to their average vulnerability and policy quality (see Fig. 6).

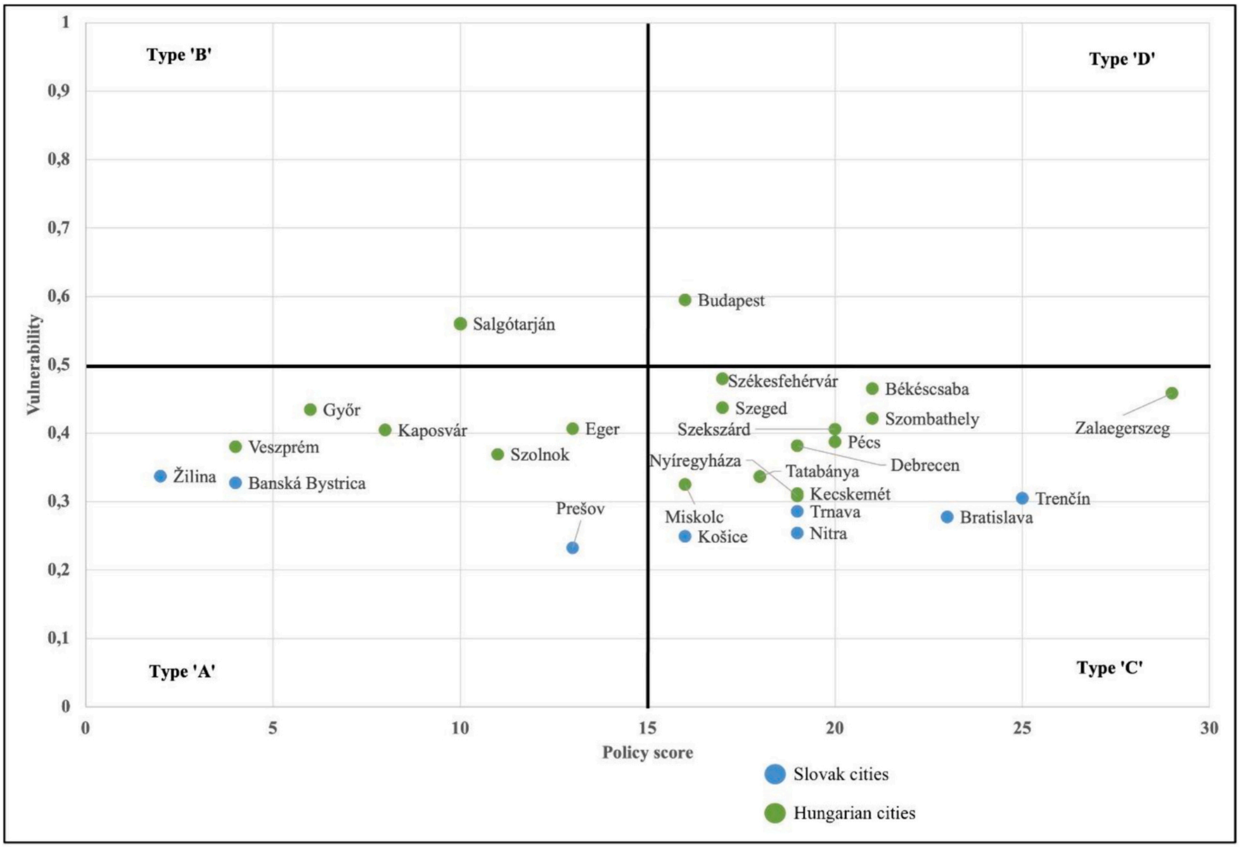

Fig. 6. Average heatwave vulnerability and climate strategy scores of selected Slovak and Hungarian cities.

3.1. Quantitative analysis: findings on heatwave vulnerability

According to our findings, Slovak regional seats show lower sensitivity to heatwaves than their Hungarian counterparts. Our comparison (see Fig. 3) reveals more favorable demographic and socio-economic characteristics in the selected Slovak cities. These include a considerably more balanced age structure, a slightly more balanced gender distribution, lower population density, and unemployment rate. However, the lowest value of heatwaves sensitivity (0,166) was observed in a Hungarian city, Kecskemét (Fig. 4). In contrast, Budapest, the capital of Hungary, has the highest sensitivity (0,645). It has the highest population and imperviousness density in our sample. Salgótarján^{H}, the second most sensitive city (0,603), is characterized by an exceptionally high unemployment rate and an older age structure.

Cities in the north-east of Hungary (Eger, Salgótarján, Miskolc) exhibit high sensitivity to heatwaves, indicating an older age structure and/or less balanced gender structure. Most of the cities in the Transdanubian region^{H} (Szombathely, Veszprém, Zalaegerszeg, Székesfehérvár, Kaposvár, Szekszárd, Pécs) have low or moderately low sensitivity performance because of their unfavorable demographic structures. Finally, the cities of the Great Plain^{H} show a lower sensitivity to heatwaves (similar to the Slovak cities), thanks to the lower density of their built-up areas.

Cities in the Southern Great Plain^{H} (Szeged, Békéscsaba), as well as cities in the northern and north-western part of Hungary (Győr, Tatabánya, Budapest, Székesfehérvár, Salgótarján), along with Debrecen and Žilina, exhibit weaker adaptive capacity to heatwaves. The lowest value of adaptive capacity (0,456) defines Budapest due to its limited access to pharmacies, green and blue areas, and swimming pools, along with just a + 1% change in tree cover density. In comparison, in Prešov^{S}, we detected the highest value of adaptive capacity (0,773) to heatwaves. It outperformed every other city in health-related indicators, i.e. in the number of pharmacies and children and adult practitioners.

In general, Slovak regional seats have better health-related conditions, while Hungarian county seats perform better in green and blue infrastructure indicators. Tree cover density in Hungarian cities showed a promising upward trend with an average 4% increase, whilst Slovakian cities experienced a 1% decrease. In comparison, Trnava^{S} has a shockingly low level of natural surface coverage. Žilina's^{S} and Prešov's^{S} remote sensing data revealed 8% and 6% reductions in tree cover density. The lack of swimming pools in Žilina^{S}, Salgótarján^{H}, and Veszprém^{H} can also make it difficult for their residents to adapt during heatwaves.

Fig. 5 demonstrates the results completed by the fuzzy method. The size and color of the diagrams represent the results achieved by the cities: the larger the circles, the more desirable the outputs are. The prominent performance of Slovak cities is apparent, except for

Table 2
Applied sensitivity indicators.

Category	Indicator	Basic rationale	Sources
Age	Ratio of people with age 65 + and 0–2 (S1) Aging index (S2)	Children and older people are more prone to heatwaves due to their poor thermoregulatory ability, and weaker capability to communicate their needs.	Buzási, 2022; Buzási et al., 2022; Dong et al., 2020; Inostroza et al., 2016; Nayak et al., 2018; Niu et al., 2021; Wolf and McGregor, 2013
Population distribution	Population density (S3)	Higher population densities in urban areas are in strong correlation with higher surface temperatures.	Arifwidodo and Chandrasiri, 2015; Buzási, 2022; Buzási et al., 2022; Mallick and Rahman, 2012; Rauf et al., 2020; Steeneveld et al., 2011; Wolf and McGregor, 2013
Sex/gender	Proportion of the female population (S4)	Women face higher health risks to heatwaves for socio-economic and physiological reasons (generally lower salaries, and aerobic power when compared to men).	Dong et al., 2020; Kazman et al., 2015;
Built infrastructure	Imperviousness density (S5)	Higher imperviousness density suggests higher intensity of the urban heat island effect.	Buzási et al., 2022, Niu et al., 2021;
Socio-economic conditions	Unemployment rate (S6)	The availability of thermal adaptation facilities in a community has been shown to correlate with the unemployment rate.	Buzási, 2022; Buzási et al., 2022; Inostroza et al., 2016; Niu et al., 2021; Wolf and McGregor, 2013

Table 3
Applied adaptive capacity indicators.

Category	Indicator	Basic rationale	Sources
Medical services	The number of pharmacies (A1) The number of children/adult practitioners (A2)	Medical facilities and resources are important for the treatment and prevention of heat-related diseases, as for maintaining the population's health.	Buzási, 2022; Buzási et al., 2022; Dong et al., 2020; He et al., 2019; Inostroza et al., 2016; Niu et al., 2021;
Green and blue infrastructure	Available green and blue areas (A3) Tree cover density (A4) Swimming pools[a] (A5)	High vegetation coverage and urban inland water have been considered to mitigate the heat island effects. Swimming pools provide a cooling and relaxing place for the population.	Buzási, 2022; Buzási et al., 2022; Gupta et al., 2019; He et al., 2019; Inostroza et al., 2016;

[a] The term ‘swimming pools’ refers to the number of artificial, constructed beaches rather than the number of pools.

Bratislava, which achieved only a medium rating. These cities have low sensitivity and relatively high adaptive capacity to heatwaves, as described before.

In the case of the Hungarian cities, there is a less homogeneous picture. Kecskemét, Nyíregyháza, and Szolnok can be considered relatively resilient to heatwaves. The majority of cities belong to the medium category, as they are not particularly strong or weak in terms of sensitivity or adaptivity. Lastly, Budapest[H] and Salgótarján[H] are relatively vulnerable to heatwaves due to their higher sensitivity and lower adaptive capacity.

A total of 5 categories would be available from the variations of the inputs. However, regarding the 27 analyzed cities, only three categories were covered based on the extent of the average results of the indicators. This may be due to the strict rulemaking process, in which the adaptation capacity and sensitivity criteria must be fulfilled together. Therefore, the average values of the inputs cannot be used to improve the output. While fuzzy logic could provide a more nuanced examination of the cities, our results demonstrate that the outputs may not always fit into the predefined categories.

3.2. *Qualitative assessment: findings on climate strategy content*

Regarding our policy assessment results (see Figs. 5 and 6; for more details, see Table 8 in the Supplementary), we conclude that five cities (19%) reached low scores, and four cities (15%) performed below the average threshold. Notably, none of the low-performing cities had set any health-related objectives. Most cities (56%) were in a moderate position, while three (11%) accomplished high policy quality. The latter (Bratislava[S], Trenčín[S], and Zalaegerszeg[H]) we identify as policy leaders regarding heat-related climate change impacts in our analyzed countries. Additionally, it is worth highlighting that Zalaegerszeg stood out from the whole sample with a nearly perfect score.

Mentioning some examples, in the case of Győr[H], their measures were briefly presented without proper justification, lacking a clear connection to the heat issue. Kaposvár[H] had a relatively shallow climate strategy, lacking in-depth analysis. The SECAP of Veszprém[H] focused mainly on mitigation and overlooked adaptation aspects, consistent with previous planning documents in Hungary. Unlike other Hungarian cities, Veszprém's Strategy remained unchanged between 2020 and 2022. Žilina[S] did not address climate change in its strategic development plan, offering only two vaguely defined measures related to infrastructure and the environment. The action plan of Banská Bystrica[S] mainly consisted of a climate change vulnerability assessment, despite its title suggesting a focus on mitigation and adaptation. It lacked specific goals and measures for addressing climate change impacts.

3.3. *Synthesis of heatwave vulnerability and climate strategy scores*

Fig. 6 plays a crucial role in clustering the evaluated urban areas. The y-axis represents the average heatwave vulnerability scores, calculated based on the sensitivity and adaptive capacity scores. A value of ‘1’ indicates high vulnerability, while ‘0’ refers to low vulnerability to heatwaves. On the other hand, the ‘x-axis represents policy scores, ranging from 0 to 30, with 30 being the theoretical maximum value. Type ‘A' cities (Veszprém, Győr, Kaposvár, Szolnok, and Eger from Hungary; Žilina, Banská Bystrica, and Prešov from Slovakia) show relatively low vulnerability. Since their policy scores do not reach 50% of the theoretical maximum, we categorize them as low-risk cities with inferior policy quality. It is worth mentioning that the assessed strategies of Žilina[S], Banská Bystrica[S], and Veszprém[H] did not reach 5 points. Type ‘B' and ‘D' represent vulnerable cities to heatwaves with less structured and focused plans. These categories include two Hungarian municipalities (Budapest and Salgótarján). Budapest has a policy score of 15, whereas Salgótarján scores only 10. Finally, Type’C′ cities also exhibit lower values of average vulnerability, but in contrast to Type ‘A' cities, they have above-average policy scores. We label them as low-risk cities with higher policy quality. While these strategies effectively address heat-related climate change impacts, continuous monitoring and evaluation are crucial for strengthening resilience to future heatwaves on their territory.

4. Discussion

The results revealed the main differences between Hungarian and Slovak cities in connection to their sensitivity and adaptive capacity to heatwaves by involving statistical and remote-sensing data. Based on the applied fuzzy method, Slovak cities exhibit a lower vulnerability to heatwaves than Hungarian cities. Despite variations in the overall values, there are no clear and consistent

Table 4
Questionnaire of the strategy assessment.

	City	Questions	Description
General intro	Heat-related assessment	G1 - Is there a detailed assessment of the heat-related situation in the city?	Climatic conditions, urban heat island effect, heat-related climate change impacts e.g. temperature increase, heat waves
	Situation analysis, e.g. SWOT	G2 - Does the situation analysis, e.g. SWOT, risk assessment refer to the heat-related issue?	Strength, weaknesses, opportunities and threats in connections to heat-related issue, e.g. high exposure to UHI
	Objective(s)	G3 - Does the strategy set objective(s) in the context of heat-related climate change impacts?	Improve microclimatic conditions, reduce urban heat island effect, adapt to heat-related climate change impacts etc.
Measures category	IT, decision support tools	M1 - Does the plan include IT or decision support measures for heat-related climate change impacts?	Digital databases, apps, decision support tools
	Warning or observing systems	M2 - Does the plan include measures related to warning or observing systems for heat-related climate change impacts?	Upgrade weather services, monitoring systems
	Practice, behavior, information dissemination	M3 - Does the plan include practical or behavioral measures (awareness rising) for heat-related climate change impacts or measures to disseminate information about them?	Education programmes, workshops, behavior-forming measures
	Built infrastructure	M4 - Does the plan include gray infrastructure measures for heat-related climate change impacts?	Residential programmes, upgrades of buildings and gray infrastructure, e.g. facade shading, passive cooling.
	Environment	M5 - Does the plan include green and/or blue infrastructure measures for heat-related climate change impacts?	Building, improving and maintaining green and blue infrastructure, e. g. public greenery, vegetation zones, green roofs
	Health and social system	M6 - Does the plan include health and/or societal measures for heat-related climate change impacts?	Healthcare and social care systems, health promotion
	Vulnerable groups	M7 - Does the plan identify certain measures on groups that are/will be particularly impacted by heat-related climate change impacts?	Informing vulnerable population groups, taking into account their specific needs
	Policy	M8 - Does the plan include urban policy measures for heat-related climate change impacts?	Climate design guidelines, heat emergency response plan, organizational development

Source: Buzási et al. (2021); Kalbarczyk and Kalbarczyk (2022). Modified by the authors.

Table 5
Applied scoring system.

General intro	2 points	Explicit, detailed and quantified heat-related information
	1 point	Indirect, general framing of heat-related information
	0 point	No or insufficient[1] heat-related information
Measures	3 points	Well-defined measure with cost estimation and identification of the implementation
	2 points	Well-defined measure without cost estimation or not clearly specified measure with cost estimation
	1 point	Under-defined[2] measure and/or a part of another measure
	0 point	No measure

Source: Buzási et al. (2021). Modified by the authors.
Notes:[1] The available information contains only one aspect of the heat-related issue, e.g., UHI.
[2] No method or specific actions included and/or lack of coupling with heat-related adaptation, e.g., increased knowledge about climate change impacts.

regional patterns within the studied areas. Regarding the policy assessment, we cannot identify such regional differences or patterns since the assessed cities show a mixed outcome. The comparative analysis of heatwave vulnerability and policy preparedness highlights Budapest[H] and Salgótarján[H] as the two most vulnerable cities. Consequently, we recommend that these cities take clear actions in order to build resilience.

As we have highlighted in the Introduction, our comparative assessments encompass a wide range of Hungarian and Slovak cities. Our findings are closely related to previously cited studies from Central Europe. While prior research sporadically dealt with urban climate issues, such as the urban heat island or thermal discomfort, our results underscore the need to scrutinize these aspects in greater detail. However, it is crucial to note that our findings stem from a comparative assessment of selected cities. Therefore, our heatwave vulnerability scores need to be interpreted concerning their relative meanings. The intensified urban heat island effect is undeniably a significant urban climate concern, particularly in the case of larger cities like Budapest. Additionally, the aging population in many cities, especially in the eastern part of Hungary, makes them more sensitive to heatwaves. This, in turn, lays the foundation for further analyses of various vulnerability aspects. Finally, it is worth mentioning that the decreasing tree cover, particularly in some Slovak cities, positions them as areas that require more thorough and focused analyses, highlighting the need for upcoming detailed analyses of microclimatic aspects to prevent a decrease in overall adaptive capacity.

Considering geographical patterns, as previously stated, we expected a north-south range of heatwave vulnerability and significant disparities in strategy scores between Slovak and Hungarian cities. Our results indicate that the first assumption is only partially valid. Even though Slovak cities have generally higher resilience than their Hungarian counterparts, regional heterogeneity in heatwave vulnerability scores from Hungary does not correlate with this direction. For example, Budapest and Salgótarján, the two most vulnerable cities, are not located in the southern part of Hungary. Regarding the policy scores, our findings unveil a heterogeneous regional pattern instead of country-specific results, as Hungarian and Slovak cities can be found at both ends of the policy preparedness score spectrum. Consequently, it cannot be established that national-level legislation or guidelines lead to a significantly uniform regional pattern. This underscores the paramount role of local factors in climate adaptation planning.

In general, Hungarian climate strategies display a structured format, following guidelines from a methodological handbook (MBFSZ, 2018). They typically include sections on situation analysis, assessment, objectives, measures, and implementation elements like monitoring, resources, and institutional parameters. Their measures are presented in well-organized tables, with a balanced approach to mitigation, adaptation, and awareness-raising. The structure of the strategies did not affect the final scores as the handbook (MBFSZ, 2018) did not ensure the same depth of analysis and measures for every climate change related aspect, like heatwaves or floods. In contrast, Slovak policy contexts tend to separate mitigation and adaptation strategies instead of combining them into climate plans. Slovak adaptation strategies often involve academic experts, resulting in comprehensive situation analyses, including heat-related data, demographic information, socioeconomic factors, and remote sensing data, presented through maps in documents from cities like Bratislava, Banská Bystrica, Košice, Prešov, Trenčín, and Trnava.

Apart from our hypotheses, we discovered significant findings, particularly concerning policy quality. In connection with the proposed measures, climate strategies place a prominent emphasis on enhancing blue-green infrastructure to ameliorate microclimatic conditions and preparing the built environment through thermal protection and shading measures. However, measures addressing vulnerable populations exhibit comparatively low popularity. Such actions predominantly revolve around cultivating attitudes and raising awareness through communication campaigns concerning heatwaves, with an additive inclusion of vulnerable individuals as a target group. Vulnerable groups do not receive any direct interventions. Although older people receive sporadic attention, individuals experiencing poverty or engaged in outdoor occupations are seldom addressed. Remarkably, Miskolc's[H] climate strategy stands out for providing a comprehensive evaluation of vulnerable groups as a distinct aspect within their situational analysis. Regardless, connected initiatives were not identified. Furthermore, despite the aim of multiple strategies (Eger[H], Miskolc[H], Tatabánya[H]) to mitigate the health effects during heatwaves, they do not include measures to promote or enhance their health and social care systems. Categories such as decision support, information technology, warning systems, and observation measures were also infrequently mentioned, indicating a relatively diminished demand for supplementary data to support decision-making processes.

It is valuable to bring attention to some outstanding good examples as well. Kecskemét[H] demonstrates the fundamental rationales behind its proposed measures, highlighting direct cause-and-effect relationships. Various cities, including Nyíregyháza[H], dedicate distinct sections within their strategies to expound upon the global evidence of climate change. Slovak cities and Szolnok[H] involved a team of climate experts to identify crucial areas warranting attention. Budapest's[H] and Košice's[S] strategy focus on enhancing public comprehensibility, resulting in a shorter length. However, this conciseness came at the expense of providing detailed content descriptions. In contrast, the urban climate policy context can be seen as outstanding in Bratislava, the Slovak capital. At the moment, it has three interdependent strategic documents related to climate change. In 2014, the city developed an adaptation strategy, augmented in 2017 with a stand-alone action plan with a more precise description of adaptation measures and a thorough vulnerability assessment accomplished in 2020. Finally, it is worth noting that Trnava's[S] adaptation strategy was created with the sole purpose of dealing with heat-related climate change impacts.

The main limitations of this study can be categorized into three primary aspects. As previously demonstrated, the initial set of city-scale indicators covered a much broader range of aspects of heatwave vulnerability. However, due to the synchronization of the Hungarian and Slovak databases, the number of applied indicators was considerably reduced. To expand the range of potential indicators, future research should include more quantitative data from publicly available remote sensing platforms. Various forms of urban climate aspects, such as normalized difference vegetation index, urban hotspots, changes in land use - land cover patterns, urban thermal field variance index, or surface urban heat island effect, could all be included in a comparative study emphasizing the role of local features regarding climate adaptation aspects. Secondly, the number of cities involved, particularly from other Central European countries, could enhance the representativeness of a future study, constituting another limitation of the present paper. However, it is important to note that including more cities from different countries may further reduce applied indicators due to inconsistencies in socio-economic statistical data sources across nations. Nevertheless, the expanded utilization of remote-sensing data may empower scholars to analyze a broader spectrum of urban areas from a highly localized perspective, encompassing aspects like heatwave-related vulnerability and other adaptation issues. As stated before, content analysis of urban climate strategies can access the rhetorical part of urban climate change adaptation. However, the effectiveness of the policies requires their application, which evidently goes beyond the scope of this study as we could not determine if the proposed measures of analyzed documents were implemented in practice. This limitation suggests that further research is needed to investigate this aspect, especially in light of Betsill and Bulkeley (2007), who characterized a persistent gap between the policy and the reality of urban climate change adaptation.

5. Conclusions

In our article, we aimed to develop and apply a comparative assessment of selected Hungarian and Slovak cities regarding their vulnerability to heatwaves and to fill a gap in the literature by focusing on a relatively under-studied area. Our methodology included an indicator-based vulnerability analysis and a qualitative policy assessment based on a predefined questionnaire that can be easily adopted by policymakers, urban development practitioners, and academics. In addition to providing insights into Central European cities that require urgent action to mitigate above-average heatwave vulnerabilities and develop more effective climate strategies, our article aimed to uncover regional patterns within the study area.

Based on our findings, we cannot identify a clear north-south direction of increasing heatwave-related vulnerability across the selected cities as we hypothesized before. Nevertheless, based on our applied methodology that included fuzzy logic as well, Slovak cities are comparatively less vulnerable than their Hungarian counterparts. Besides quantitative results, we paid attention to the quality of plans by assessing the effectiveness of urban climate adaptation strategies. In this case, we could also not identify any country-specific patterns, only heterogeneous regional characteristics. However, we analyzed the selected plans in detail by pointing out the strengths and weaknesses of the documents and addressing practical aspects. Furthermore, we emphasized the parallel interpretation of quantitative and qualitative results, as above-average vulnerability scores should accompany high policy effectiveness to avoid misallocating finite human and financial resources in policymaking.

CRediT authorship contribution statement

Renáta Farkas: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Anna Csizovszky:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Bettina Szimonetta Beszedics-Jäger:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Attila Buzási:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Investigation, Funding acquisition, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Grammarly in order to improve readability and language. After using this tool/service, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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