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Assessing heatwave resilience in municipalities around Lake Balaton: A comparative analysis

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Abstract

Changing climate patterns represent a major challenge for Hungarian municipalities, particularly with regard to the increasing severity and frequency of heatwaves. As a result of the COVID-19 lockdowns, thousands of people moved to communities around Lake Balaton; therefore, cities and villages should place more emphasis on their long-term sustainability and climate resilience. This article addresses the literature gap in assessing the heatwave resilience of Hungarian settlements, focusing on the municipalities of the Lake Balaton Resort Area. Our main objective was to uncover spatial and temporal patterns in the 180 settlements involved in the analysis by using an indicator-based comparative method. The set of indicators included nine sensitivity and six adaptive capacity measures referring to the base years 2015 and 2022. Our results show heterogeneous spatial patterns across the analysed categories; however, several regional clusters can be identified: 1) in general, settlements from the northern part of the study area had above-average adaptive capacity, while the southern and south-western municipalities had significantly lower values, 2) only one micro-regional cluster can be defined in terms of sensitivity values in the northern part of the study area; 3) below average resilience values were found in the south-western and southern areas; 4) finally, neither sensitivity nor adaptive capacity nor overall resilience scores had changed significantly over time at the regional level. The applied methodology can easily be adopted in other Hungarian or even Central and Eastern European cities; consequently, new results can contribute to a better understanding of inter- and intra-regional patterns of heatwave resilience at the local level.

Keywords: heatwave resilience, adaptive capacity, municipalities, Lake Balaton, Hungary

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Introduction

Climate change is significantly impacting almost every settlement in the world by increasing the magnitude and frequency of extreme weather events (Wamsler, C. *et al.* 2013; IPCC 2018, 2021). Although the challenges are global, local-level solutions and detailed analysis are required to effectively increase the resilience of various stakeholders (Aboagye, P.D. and Sharifi, A. 2023). The number of publications addressing aspects of climate resilience at the local level has increased significantly in recent years (Woodruff, S. *et al.* 2021; Datola, G. *et al.* 2022), as the need for local governments to strengthen their capacities and develop their own climate policies increases (Reckien, D. *et al.* 2023). The dynamically changing external factors require quantitative and qualitative approaches to increase the co-benefits of mitigation and adaptation activities (Sharifi, A. 2021); also to avoid unintended long-term effects, so-called lock-ins (Ürge-Vorsatz, D.. *et al.* 2018; Buzási, A. and Csizovszky, A. 2023). In general, vulnerability and resilience-oriented topics have received increasing attention in academia, particularly with

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regard to heatwave-related challenges (Tong, P. 2021; Kiarsi, M. *et al.* 2023). There are numerous works in the literature that demonstrate the relevance of heatwave-related resilience factors through cross-country comparisons or individual assessments (Alonso, L. and Renard, F. 2020; Arshad, A. *et al.* 2020; Shi, Y. *et al.* 2021). The growing body of literature contributes to a better understanding of the general characteristics of heatwave resilience at the local scale. However, since adaptation problems strongly depend on local characteristics, there is undoubtedly a need to carry out comparative assessments at the regional level in order to deepen the existing knowledge about problems at the local level.

According to regional climate models, Hungary is facing significant changes in climate patterns: an increasing number of days with heatwaves (Torma, C.Z. and Kis, A. 2022; Simon, C. *et al.* 2023) when the average daily temperature exceeds 25 °C (Uzzoli, A. *et al.* 2018), and heavy rainfall (Jakab, G. *et al.* 2019; Schmeller, G. *et al.* 2022) are expected. Apart from these external factors, numerous indicators dealing with social issues point to potential sustainability problems: a decreasing size of the total population, a negative migration balance, especially in small settlements (Ritter, K. 2018), or an aging population (Menyhárt, O. *et al.* 2018) all contribute to the increasing vulnerability of the Hungarian society (Uzzoli, A. *et al.* 2018). However, more papers can be found in the literature that address local climate adaptation issues in Hungarian settlements from different perspectives (Li, S. *et al.* 2017; Patkós, C. *et al.* 2019; Szalmáné Csete, M. and Buzási, A. 2020 Szalmáné Csete, M. and Buzási, A. 2020; Kiss, E. *et al.* 2022; Jäger, B.S. and Buzási, A. 2023), it can be noted that comparative analyses involving a higher number of Hungarian municipalities are still almost completely missing, which represents a relevant literature gap. The same argument was put forward (Ferenčuhová, S. 2020) by analysing the existing literature on post-socialist cities in light of the challenges related to climate change. It is explained that current studies focusing on the local level of Central and Eastern Europe are quite rare and underdeveloped. Consequently, further studies and critical assessments are needed to improve the capacity of local stakeholders to address the negative impacts of climate change. Local governance and related bodies play a crucial role in reducing vulnerability at the settlement level by making climate change adaptation more integral to everyday decision-making and planning practices (Óvári, Á. *et al.* 2023). However, limited capacity in climate governance has been revealed by Óvári, Á. *et al.* (2024), therefore, the analytical assessment of non-planning aspects of Hungarian settlements can contribute to a better understanding of the local status of resilience production practices.

Therefore, our paper aims to analyse the heatwave resilience of a large number of Hungarian settlements by applying an indicator method. In this topic, a limited number of previously published papers can be found in the literature.

This paper focuses on the municipalities surrounding Lake Balaton, the so-called Lake Balaton Resort Area (*Balaton Kiemelt Üdülőkörzet* in Hungarian, and its short form "BKÜ" in the following), which involves 180 settlements. Lake Balaton has been the focus of numerous works from different scientific areas, however, the local level is rarely studied as the lake itself is taken into account instead. Most commonly, water quality and related problems, challenges, and potential opportunities have been analysed in terms of climate change (Kutics, K. and Kravinszkaja, G. 2020; Istvánovics, V. *et al.* 2022) or human activities as main drivers and their impacts on water balance (Rizk, R. *et al.* 2021; Kocsis, M. *et al.* 2024). In addition to the natural science studies, several papers addressed more holistic sustainability issues: Pomucz, A.B. and Csete, M. (2015), and Lőrincz, K. *et al.* (2020) analysed various aspects of sustainable tourism considering the Balaton region; Marton, I. (2006) developed a set of indicators to describe complex development patterns at the community level; Molnár, T. and Molnár-Barna, K. (2019) assessed settlements in Veszprém County from a development policy perspective; finally, Obádovics, C. (2020) provided population development forecasts in the Balaton resort area and argued that the proportion of people over 65 years of age could reach 35 percent by 2062. This latter analysis sheds light on the importance of climate-related assessments in the region, taking into account the continuously aging population.

The present paper reflects the literature and scientific gap by analysing the resilience patterns of the municipalities of BKÜ. The scientific novelty of this paper is based on the study area since similar research focusing on these settlements cannot be found in the literature, especially not with regard to heatwave resilience. Secondly, the applied set of indicators derives from publicly available databases; therefore, it can easily be adapted to other Hungarian settlements or regions. Finally, our analysis not only provides a snapshot of resilience values but uses data from 2015 and 2022 can also reveal spatiotemporal patterns that also contribute to identifying regional differences and hotspots.

Literature review

In the pages of the Hungarian Geographical Bulletin, there are several examples where scientists focused on climate adaptation issues at the local level. One of the first results was published by Gál, T. *et al.* (2016) and analysed urban heat island patterns in Szeged using different local climate zones. According to their results, dense urban areas are significantly hotter, than surrounding zones, which is a thought-provoking result given the increasing development rate in the BKÜ settlements over the last 10 years. Since the study area is associated with Lake Balaton as an attractive tourist destination (Medarić, Z. *et al.* 2021), the tourism sector and its vulnerability are relevant factors to be analysed in previously published works. Csete, M. *et al.* (2013) found that the Lake Balaton region has medium vulnerability with above-average exposure, which is, however, complemented by high adaptive capacity. A more recent article from the Hungarian Geographical Bulletin (Kovács, A. and Király, A. 2021) assessed the climate exposure of tourism in Hungary and argued that a significant decline in climatic conditions is observed in summer - precisely the time when most tourists arrive in the surrounding settlements at Lake Balaton and possibly worsened the resilience of the communities. Since an intensive urbanization process can be seen in numerous settlements from the BKÜ, those studies that focused on microclimatic peculiarities in the sense of different or changing land use patterns should be mentioned. Gál, T. *et al.* (2021) analysed various cities in the Carpathian Basin regarding their thermal comfort issues in light of changing climate patterns in the 21st century. Their results indicate that an increase in the number of tropical nights is associated with densely populated urban areas compared to rural areas. Since Szeged is one of the most studied Hungarian cities with regard to the challenges related to climate change, another article by Kolcsár, R.A. *et al.* (2022) analysed the urban green space provision of different population groups. Since urban green spaces play a crucial role in mitigating the severity of heatwaves. In addition, it is assumed that the settlements around Lake Balaton will become more urban in the future. Finally, intensive urbanization contributes to an exacerbation of the urban heat island effect, which disproportionately affects the local population, as shown Szemerédi, E. and Remsei, S. (2024) in the case of Győr.

At the LAU-1 level, two comprehensive assessments can be found in the literature (Uzzoli, A. *et al.* 2018, 2019) that focus on micro-regional differences in heatwave vulnerability patterns in Hungary. The set of indicators used consists of exposure, sensitivity and adaptive capacity indicators based on public databases. Second, Farkas, J.Z. *et al.* (2017) provided a detailed analysis of climate vulnerability at the regional scale by focusing on the Southern Great Plain and including more than 250 settlements in their studies. In addition to the results of regional climate models, the authors also measured the ecological and socioeconomic aspects of climate vulnerability using the CIVAS model (Pálvölgyi, T. and Czira, T. 2011). One of the most recent settlement-scale studies addressing climate vulnerability was developed by Lennert, J. *et al.* (2024), who adopted the CIVAS model to develop a multi-indicator method that assesses exposure, sensitivity and adaptive capacity at a local level taken into account. The results show an above-average risk to settlements around Lake Balaton. Therefore, it prepares the ground for the present study to highlight the spatiotemporal dynamics of these settlements in terms of their heatwave resilience.

Methodology

The study area is located in western Hungary, embedded between the central and southern Transdanubian NUTS 2 region *(Figure 1).* At its heart lies Lake Balaton, a natural wonder and the largest freshwater lake in Central Europe. Within this area, there are 45 coastal settlements, 7 of which are directly adjacent to the coast and 128 of which have no direct access to it. The BKÜ includes 180 towns in the three counties of Veszprém, Somogy and Zala. According to the Hungarian Central Statistical Office database, the total population of the BKÜ is about 270,000 people, occupying an area of about 3,884 km². Several important cities shape the region's landscape: Balatonalmádi, Balatonfűzfő and Balatonfüred are rapidly developing urban centres on the north-eastern shore of Lake Balaton. Notable attractions on the western side include Tapolca, known for its natural treasures such as sea caves, and Keszthely, the third largest city in Zala County, which serves as a centre for culture, trade and education in the region. In the southeast, Zamárdi and Siófok offer special attractions. Zamárdi hosts various festivals, while Siófok offers a wealth of permanent events that appeal to both tourists and locals. The towns in this defined area have a vibrant culture and benefit from excel-

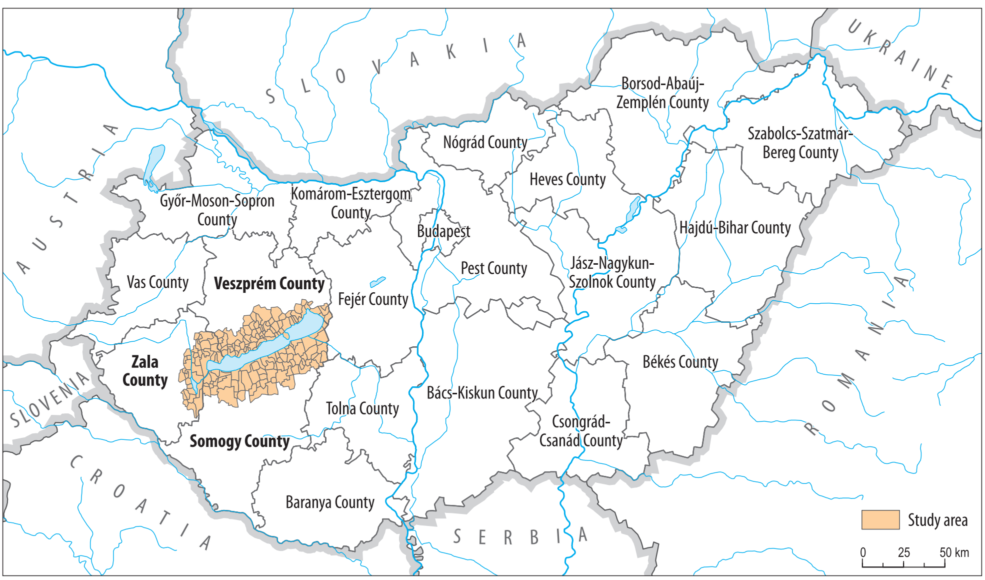

Fig. 1. The study area situated around the Lake Balaton

lent natural conditions, making them popular destinations for residents and visitors alike.

In the following paragraphs, the socio-economic background of the study area is introduced by emphasizing selected statistical data. Firstly, the social composition of Hungary is characterized by aging and this phenomenon can also be observed in the study area *(Figure 2).* In 2015, Kisberény had the lowest aging index, with 38 elderly people per 100 children and minors. This year, Szigliget had the highest number of people aged 65 and over with 416.4 per 100 children and minors – the highest in the region. However, by 2022, this number had declined as the number of young people and children increased from 61 to 75, while the number of older people also increased from 254 to 279. In 2022, Tikos had the lowest aging index with 28 elderly people per 100 teenagers and children. Notably, Tikos reduced its aging index from 2015 to 2022 as the number of young people and children increased from 17 to 42, while the number of older people decreased by 3. Meanwhile, in Balatonszepezd, the aging index increased from 305 in 2015 to 559 in 2022, indicating a significant increase in the proportion of elderly people compared to children and adolescents. Overall, the aging index in the study areas was calculated as 167 in 2015, rose to 197.40 in 2022. It is worth noting that the National Aging Index was 123.6 in 2015 and 142.5 in 2022, according to the Hungarian Central Statistical Office.

Secondly, the number of taxpayer under HUF 300,000 annual consolidated tax base income band per year allows us to draw conclusions about the financial situation of the area, as the more people there are, the more people live in extreme poverty. Among the municipalities in the study area, Siófok had the highest population included in the indicator for both 2015 and 2022. However, it is encouraging to note that this number has decreased from 2,313 in 2015 to 2,151 in 2022. In 2015, the municipality of Óbudavár had no residents in the lowest income group, but by 2022 the number had increased to 10. In 2022, Kékkút had the fewest inhabitants living in extreme poverty, with only 4 residents, down from 13 in 2015, indicating an improvement in its situation. In the entire study area, 24,170 people belonged to this poverty group in 2015; by 2022 the number fell to 22,731. At the national level, 681,765 people belonged to one of the most vulnerable social groups in 2015, with the number decreasing slightly to 674,536 by 2022. If we

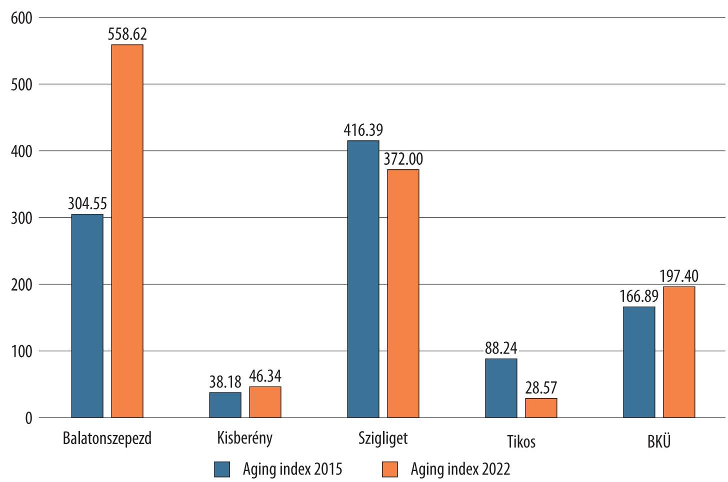

Fig. 2. Aging index in selected settlements from the study area. *Source*: Compiled by the authors.

examine the study area in the national context, we see that 3.54 percent of the country's population in 2015 in the income range under HUF 300,000 lived and this percentage fell to 3.37 percent by 2022.

From a climate policy perspective, it is worth noting that several settlements are members of a Hungarian umbrella organization, the so-called Alliance of Climate-Friendly Settlements: Balatonfőkajár, Küngös, Zalaszántó and Gyenesdiás. However, this does not mean that every municipality has a publicly available climate strategy; nevertheless, Gyenesdiás and Tapolca have uploaded their thematic strategies to public websites. Both policies have focused on extreme heat events with varying degrees of emphasis, although Tapolca pays much more attention to this issue. In addition, Balatonfüred, Tab and Zalacsány are signatories of the Covenant of Mayors of Europe with available Sustainable Energy and Climate Action Plans or climate strategies, which distinguish heat waves as one of the most serious threats to everyday tourism, alongside above-average vulnerability of lake shores.

The applied assessment methodology is based on the 2014 IPCC framework. We selected social, environmental and economic data from the National Spatial Development and Planning Information System (TeIR), that formulate sensitivity and adaptive capacity indicators, which would be separated into sensitivity and adaptation indicator groups. The observed years were 2015 and 2022; the starting date refers to the last year when the list of BKÜ settlements was finalized (when Balatonkenese and Balatonakarattya were divided); moreover, 2022 has begun an endpoint in this analysis due to the full availability of statistical data. *Table 1.* summarizes the applied set of indicators, representing their names, units of measure, and years.

Sensitivity indicators reflect the intrinsic characteristics of a particular system in terms of climate change; therefore, sensitivity value indicates the negative or positive effects of climate change affecting the system both directly or indirectly (Füssel, H.M. and Klein, R.J.T. 2006). The indicator "number of residents per general practitioners" shows the workload of doctors. When the indicator is high, doctors cannot efficiently care for locals suffering from diseases caused by climate change. People aged 0-2 and 60+ years are sensitive to the negative effects of climate change, such as heat waves (Smith, C.J. 2019). According to several European and North American studies, there is a positive association between heat waves and mortality, with older people and women at greatest risk (McMichael, A.J. *et al.* 2006). Nowadays, natural gas is a critical resource in Hungary due to its quantity and price. We assumed that the price of the resource is high, and locals then have to pay a higher share of their income, which reduces the well-being of the population, leading to lower adaptive capacities.

The next indicator was the total number of municipal green spaces in relation to the size of the settlement. Green spaces have numerous benefits from a sustainability and climate adaptation perspective: they provide natural shade, increase urban biodiversity, reduce the urban heat island effect (Szabó, B. 2015), protect against UV radiation, and thereby reduce numerous health problems (Coutts, C. and Hahn, M. 2015). The smaller the green area, the greater the sensitivity of the settlement; however, it is worth noting that the indicator we applied in this paper only refers to green spaces owned by the municipality. In addition, there may also be privately owned green spaces in the municipality, which can change the status of the indicator. The indicator of the ratio of taxpayers for an annual tax base under 300,000 HUF reflects the number of the poor population, which may be economically and socially sensitive. This population cannot move away or recover from climate damage due to lower income; in addition, the health of poorer people is at greater risk from extreme weather events (Sarkodie, S.A. *et al.* 2022). The number of heat wave days is expected to increase, which will also have a negative impact on people with cardiovascular diseases, which is why

Table 1. The applied set of indicators for 2015 and 2022

Indicator type	Name of indicator	Unit
Sensitivity	Number of residents per general practicioners	person
	Proportion of people aged 0–2 and 60–x in relation to the resident population	%
	Gas supplied for households (without conversion)	m^3
	Total municipally-owned green areas in relation to the size of the settlement	%
	Ratio of taxpayers for under HUF 300,000 annual tax base	%
	Per capita sales of medicines purchased for circulatory diseases	person
	General practitioner attendances and visits per capita	person
	Number of newly built flats / 1000 flats	pcs
	Population density	ppl/km^2
Adaptive capacity	Total municipally-owned green areas per capita	m^2/capita
	Net domestic income per capita	HUF
	Forest land per capita	ha
	Electricity supplied to households	kWh
	Passenger cars per 1000 capita	pcs
	Number of pharmacies and branch pharmacies per 100 capita	pcs

Source: Compiled by the authors.

the health of city residents is also sensitive. Therefore, we used an indicator of per capita sales of drugs for circulatory diseases and per capita attendance and visits to general practitioners, as the high values may indicate poor health and reflect a high level of sensitivity.

Adaptation is the ability to help systems, institutions, and people adapt to the negative impacts of climate change and also provide the means to respond to the consequences (Sharma, J. and Ravindranath, N.H. 2019). Since the study area faced above-average population growth during the first years of the COVID-19 pandemic, two statistical data (the number of newly built flats per 1000 flats; population density) refer to the related challenges from a social perspective.

As we mentioned in the previous part of this study, green spaces, and forests can improve the adaptive capacity of the analysed municipalities. Reforestation of slopes prevents landslides and the growth of green spaces creates a comfortable environment against heat waves (Donatti, C.I. *et al.* 2020). In order to describe the adaptive capacity of the selected settlements, indicators for the total municipal green space per capita and the forest area per capita were selected; higher values of both indicators mean improved adaptive capacity. An indicator of net domestic income per capita is an economic index that can reflect the well-being of local residents. In this case, the higher income of locals indicates higher adaptive capacity. As previously mentioned, heat wave days are expected to increase, and these negative impacts will be stressful for locals; therefore, we aimed to monitor this effect using the household electricity indicator. Our hypothesis is that a higher electricity supply leads to households using air conditioning, which helps reduce heat stress. On the other hand, we must highlight that air conditioning has two negative effects, both of which increase the sensitivity of settlements. First, they increase the urban heat island effect and are associated with enormous energy consumption, which is a problem when the energy does not come from renewable sources (Lundgren, K. and Kjellstrom, T. 2013). Resilience and mobilization can increase adaptability because, during heat stress, which can cause illness, locals can more easily reach another city with a hospital. For this reason, we chose the indicator "passenger cars per 1000 per capita", where a higher number of indicators means higher mobilization and, therefore, increased adaptive capacity. As already mentioned, the negative effects of climate change can affect the health of local people, which can be a major social and economic problem. Therefore, a well-developed health infrastructure is very important and also ensures an above-average ability to cope with the adverse effects of climate change. To highlight the situation in municipalities, the indicator "number of pharmacies and branch pharmacies per 100 capita" was used, with a lower value indicating a lower level of adaptive capacity.

In this study, we applied a weighted indicator-based approach consisting of socio-economic and environmental data from publicly available data sources by adopting the IPCC 2014 framework of climate change vulnerability assessments. From the selected statistical data, we constructed different indicators for 2015 and 2022 and then categorized them into adaptation and sensitive indicator groups. We first calculated the minimum and maximum values of the indicator for the observed years and then normalized the indicators for each city. To facilitate comparison, the indicators were sorted into a range from 0 to 1 using the following equation:

$$x' = \frac{x - \min(x)}{\max(x) - \min(x)}, \qquad (1)$$

where x' is a normalized value, x is the value of the official indicator, *min(x)* and *max(x)* are the minimum and maximum values of the indicator. If the value of indicators showed lower resilience (Number of residents for one doctor, Proportion of people aged 0–2 and 60-x in relation to the resident population, Gas supplied for households (without conversion), Ratio of taxpayers for under HUF 300,000 annual tax base, per capita sales of medicines purchased for circulatory diseases. General practitioner attendances and visits per capita), we used the following equation:

$$x' = 1 - \left(\frac{x - \min(x)}{\max(x) - \min(x)}\right), \qquad (2)$$

We scaled the indicators in the range 0–l so that the settlements could be compared. For adaptation, a value of 0 indicates low adaptive capacity, and a value of 1 indicates this feature higher. For sensitivity, the value 0 represents high sensitivity, and the value 1 represents low performance. Then, we separated the adaptation and sensitivity indicators for the observed years 2015 and 2022 by calculating the average of the adaptation and sensitivity indicators and then averaged the average values of the adaptation and sensitivity indicators to obtain a resilience score for 180 settlements. For the overall calculated resilience score, a value of 0 means low abilities and a value of 1 means the opposite, representing a resilient settlement.

Results

In this section, we present our results using QGIS to better visualize the regional patterns we can reveal and identify based on the calculated categories. It is important to note that municipalities are ranked on a scale of 0 to 1. Values close to 0 indicate low adaptive capacity and resilience with high sensitivity, while a value of 0.5 indicates moderate levels of adaptive capacity, sensitivity and resilience. The analysed settlements were divided into different colour groups; those with values around 0 were shown in red, while those around 0.5 were shown in blue. It is noteworthy that there were minimal differences between the calculated normalized values of the municipalities. Consequently, settlements were generally ranked at around 0.5, facilitating comparisons between them.

The sensitivity values from 2015 and 2022 show minimal regional clustering; however, several spatial trends can be identified. First, northern settlements, especially those in the first and second tiers from the lake shore, are generally more sensitive than those in the southern part. Sensitive clusters are notable on the western side of the Tihany Peninsula, particularly around the north-western basin of Lake Balaton. A common feature of the most sensitive settlements is the frequent absence of general practitioners; in the applied methodology, we assigned a value of "0" when the number of residents per GP and the number of GP attendances and visits were zero, indicating the highest level of sensitivity due to the lack of available healthcare services. Furthermore, the proportion of municipal green spaces was, in many cases, below average, reflecting a lower ability to contain heatwaves in these settlements. Apart from these similarities, the most sensitive settlements have different weaknesses across all indicators, without any clear clusters emerging between them. With regard to the change in values over time, *Figure 3* shows a relatively stable situation without any significant shifts in the relative positions of the municipalities.

The spatial characteristics of the adaptive capacity values are fundamentally different from the sensitivity performances discussed previously *(Figure 4).* However, a limited number of settlements along the northern border of the study area may be characterized by low sensitivity and relatively high adaptive capacity, making them among the most resilient in the BKÜ. In general, northern coastal communities have significantly greater adaptive capacity compared to their southern counterparts, particularly those settlements further from the lake. A clearly defined collection of above-average values can be seen around the Káli Basin, west of the Tihany Peninsula. This area is characterized by high well-being factors, which is consistent with the existing literature: the higher the well-being, the greater the ability to deal with the negative impacts of climate change. Micro-regions with low adaptive capacity can now be identified in the southwest corner and the southern part of the study. Similar to the highly sensitive

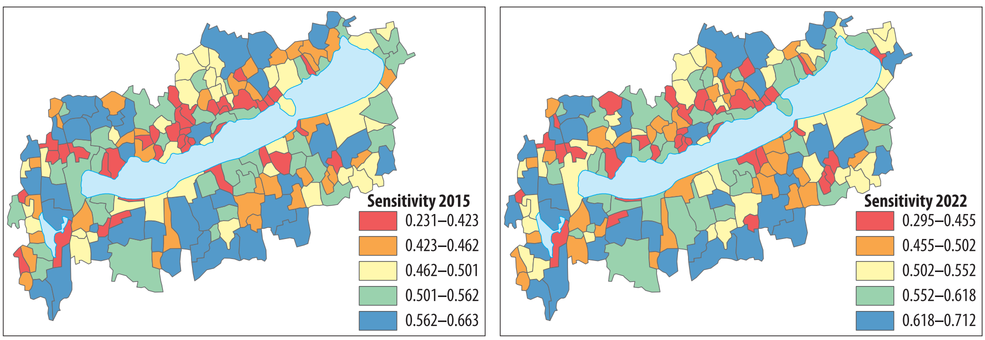

Fig. 3. Sensitivity averages for the settlements of the study area, 2015 and 2022. *Source*: Compiled by the authors.

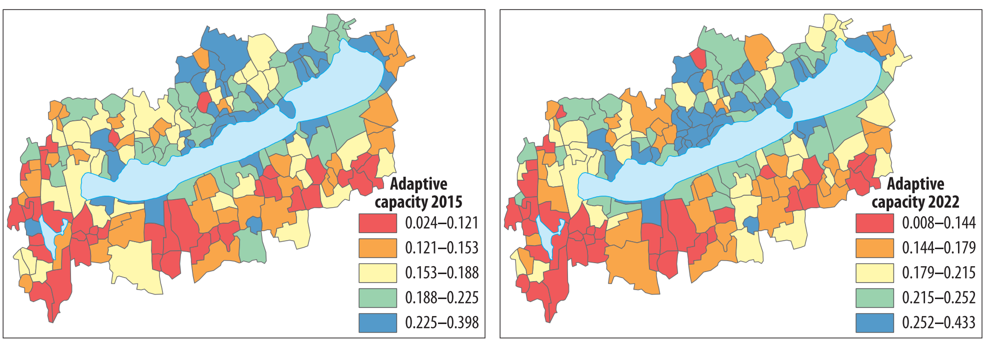

Fig. 4. Adaptive capacity averages for the settlements of the study area, 2015 and 2022. *Source*: Compiled by the authors.

settlements, two indicators contribute to the low adaptive capacity of these communities: public green spaces and the lack of pharmacies. Consequently, it is evident that poor healthcare and limited public green spaces are the main contributors of reduced resilience to extreme heat events in the region.

Since resilience values are based on the averages of sensitivity and adaptive capacity categories, no large regional clusters were identified in either 2015 or 2022 *(Figure 5)*. However, highly resilient clusters of settlements were observed in three areas: 1) along the northern lakeside, west of the Tihany Peninsula; 2) in the north-western corner of the study area; and 3) on the opposite side of the first cluster, in some municipalities further from the lake. Meanwhile, two intraregional clusters, consisting of relatively small villages in the south-western and southern regions, exhibited the lowest resilience. As it was seen regarding sensitivity and adaptive capacity categories, the overall resilience values and quintiles remained relatively the same without huge changes over the analysed 7 years.

Discussion

In addition to the regional resilience patterns we previously identified, the relationship between population size and sensitivity, adaptive capacity and resilience requires further investigation. Using normalized data, R^2 correlation coefficients were calculated for 2015 and 2022, as shown in *Table 2*. The analysis shows that there is no significant correlation between population size and the analysed resilience dimensions. This suggests that local characteristics and related socioeconomic factors play a more important role in determining resilience at the local level. This finding is consistent with the nature of climate adaptation, where the effectiveness of responses largely depends on local characteristics and tailored solutions to standardized climate-related challenges. Our results highlight the importance of locality, as evidenced by cases where settlements from the highest and lowest quintiles in terms of sensitivity, adaptive capacity, and resilience are situated next to each other, despite facing similar challenges.

Our study has several limitations regarding the applied methodology. The first cohort of limitations relates to the selected indicators due to their limited availability in our analysis. The set of indicators would be

Table 2. Correlation coefficients between population size and the analysed categories

Category	Year	R^2 values
Sensitivity	2015 2022	0.152 0.160
Adaptive capacity	2015 2022	0.112 0.148
Resilience	2015 2022	0.075 0.028

Source: Compiled by the authors.

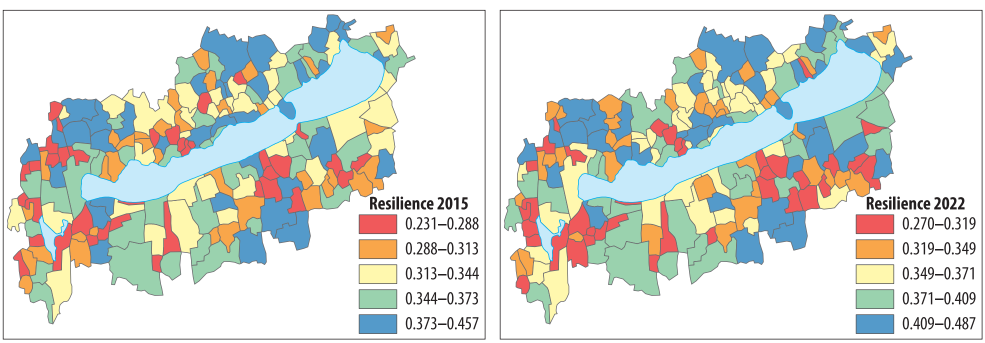

Fig. 5. Resilience averages for the settlements of the study area, 2015 and 2022. *Source*: Compiled by the authors.

expanded to include measures highlighting the speed and effectiveness of emergency responses, the availability of higher-level health facilities, and heatwave-related mortality and morbidity incidence, to name just a few statistical indicators. Apart from this, it would be useful to study land use and land cover dynamics over a longer period of time to identify the changes in artificial and natural areas that play a crucial role in identifying vulnerable settlements. The second limitation has its origins in the comparative nature of our analysis. Although the selected indicators are available for all settlements, a comparative study always encounters significant limitations due to the very different sizes and capabilities of the settlements. In our study, the number of municipalities analysed is 180, meaning that settlements with inherently different socioeconomic, environmental and institutional backgrounds were involved. Consequently, the calculated resilience, sensitivity and adaptive capacity values should be interpreted with this limitation in mind and accept the fact that all colours and values are based on the study area and do not have universal meaning.

In addition to the limitations mentioned here, some future research directions can also be identified: 1) detailed analysis of land use and land cover changes over time using remote sensing data for all settlements; 2) calculation of heatwave-related mortality to reveal regional patterns in the most vulnerable communities.

Conclusions

The aim of this study was to analyse the heatwave resilience of BKÜ settlements by using a set of indicators, including aspects of sensitivity and adaptive capacity. For this purpose, we collected social, economic and environmental statistical indicators from the National Information System for Spatial Development and Planning; then, average values for each category were calculated using the normalization method to compare and synthesize different units. Our dataset covered the years 2015 and 2022 to analyse changes in individual values and regional patterns over time. The number of assessed settlements allowed us to draw conclusions about the applicability of our methodology with a view to a possible future analysis of Hungarian settlements: it can be noted that all indicators are available at the local level; therefore, the calculations can be easily repeated to assess heatwave aspects in the Carpathian Basin. Our results also shed light on previously unknown regional patterns.

Regarding the adaptive capacity values, the northern part of the BKÜ can be characterized by higher values, while the southern and west-south micro-regions had below-average values and, therefore, lower adaptive capacity. However, intraregional clusters cannot be formulated in either 2015 or 2022. Furthermore, these values appeared to be quite stable over time. Finally, the overall resilience values showed the same spatial characteristics over time: north-eastern and north-western settlements were less vulnerable, while south-western communities can be characterized as less resilience to heatwave problems. Our study can pave the way for further analysis of the heatwave resilience of different Hungarian cities and villages based on the easy-to-apply methodology and country-specific set of indicators. Although there is an emerging gap in the literature in this research area, this paper can contribute to filling this gap and drawing the attention of policy makers to climate adaptation aspects on a local level as a new input for planning processes.

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