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Original Research Article

Assessing the Urban Climate Resilience of Cities in Hungary Using an Index-based Approach

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ABSTRACT

Climate resilience in urban areas is increasingly critical in the face of climate change, particularly in regions where climate variability poses significant challenges. This study introduces the Climate Resilience Index for Town Sustainability, a novel, multidimensional framework designed to evaluate the resilience of 19 Hungarian cities, including Budapest and county capitals. The framework incorporates 41 parameters across environmental, social, and infrastructural dimensions, addressing significant gaps in existing resilience assessments by providing a region-specific, holistic evaluation. The research employs advanced statistical techniques, including principal component analysis and k-means clustering, to analyse the data sourced from the Hungarian Central Statistical Office and the National Adaptation Geo-Information System. This analysis revealed substantial variability in resilience scores among Hungarian county capitals, with Békéscsaba achieving the highest scores due to its extensive green infrastructure, renewable energy adoption, and lower proportion of vulnerable populations. In contrast, Budapest recorded one of the lowest scores, highlighting challenges such as limited green spaces, high population density, and elevated energy consumption. Clustering analysis grouped the cities into eight distinct categories, emphasising the role of geographic and climatic factors in shaping urban resilience. The findings demonstrate the critical importance of targeted interventions, such as expanding green infrastructure, improving energy efficiency, and enhancing sustainable practices. By offering actionable insights for policymakers, this index not only advances resilience research but also provides a replicable framework adaptable to other regions. Its innovative approach to integrating multidimensional parameters represents a significant contribution to the understanding and improvement of urban climate resilience in a changing world.

KEYWORDS

Climate change, Urban resilience, Index-based analysis, Sustainability, Adaptation, CRITS index.

INTRODUCTION

In this study, resilience is defined according to the IPCC AR6 Glossary [1] as 'the capacity of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganising to maintain their essential functions, identity, and structure' This definition underscores the importance of maintaining system functionality

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and identity in the face of challenges, aligning closely with the objectives of climate adaptation and urban sustainability.

The notion of climate resilience [2] refers to the ability of a system [3], whether individual or collective, to adapt to changing climate conditions and recover from climate change damage. It also involves the capacity to continue functioning and evolving while finding solutions and strategies to address climate change challenges. The importance of climate resilience [4] lies in its ability to help reduce the impacts and risks of climate change and increase social and economic resilience and stability in changing circumstances. Enhancing resilience to climate change is essential for enabling individuals and societies to adapt to evolving climate conditions, recover from climate-related impacts, and maintain functionality and stability in the face of future challenges [5]. As cities and urban areas are particularly vulnerable to climate-related shocks and stresses, increasing resilience has become a key objective of adaptation and mitigation efforts outlined by IPCC WGIII [6]. Frequently used terms such as 'climate resilience', 'climate proofing' and 'resilient city' emphasise the idea that cities, urban systems and urban constituencies need to be able to recover quickly from climate-related shocks and stressors. Climate change poses significant challenges and risks for urban areas, such as an increase in extreme weather events and impacts on ecosystem services [7]. Effectively addressing these challenges requires an integrated modelling approach to assess climate change impacts on urban extremes and ecosystem services. This approach involves combining different models that simulate climate, urban dynamics, and ecosystem processes to understand the complex interactions and feedback between climate and urban systems [8]. Chohan *et al.* [9] investigated the climate resilience of traditional adobe-built mansions in the UAE, highlighting the Al Midfa manor's thermal efficiency and sustainability. Simulation-based improvements, including new glazing and cellulose insulation, enhanced energy efficiency while preserving the building's aesthetics, demonstrating the resilience potential of traditional housing designs.

Climate resilience indexing involves quantifying and contrasting the capacity of various regions or societies to adjust to the challenges posed by climate change. Studies have proposed indices tailored to specific contexts to develop a comprehensive Climate Resilience Index (CRI). Several indices and models have been created in the literature to understand and measure the level of resilience (**Table 1**).

Asmamaw *et al.* [10] introduced the Climate Resilience Index based on absorptive, adaptive, and transformative capacities to assess the resilience of households to climate change-induced shocks in Ethiopia. The primary determinants of climate resilience were accessibility to livelihood resources, income diversification, infrastructure, and social capital. Limited resilience was attributed to recurrent shocks, underdeveloped public services, and limited livelihood strategies. Moreover, Sono *et al.* [11] constructed the Composite National Climate Resilience Index (CNCRI) for Sub-Saharan Africa, offering a metric-based approach to assess climate resilience at a national level. The study evaluated the climate resilience of the countries in Sub-Saharan Africa using a set of 40 indicators (in five dimensions: social, economic, infrastructural, environmental and institutional). Multiple studies have introduced new tools and approaches for evaluating resilience across various contexts to create a Climate Resilience Index. One prominent framework is the Climate Disaster Resilience Index (CDRI), which has been utilised in various studies to evaluate urban resilience. For instance, Mukherjee *et al.* employed the CDRI to assess the resilience of urban slums in Barishal, Bangladesh, showcasing its utility in measuring urban disaster resilience [12]. This index is designed to capture the multifaceted nature of urban resilience, including social, economic, and infrastructural dimensions. The Climate Disaster Resilience Index (CDRI) encompasses five dimensions, 25 parameters, and 125 variables, addressing key aspects of urban disaster resilience with a focus on interrelated city services. For instance, the physical dimension – covering roads, electricity, housing, sanitation, waste disposal, and water – emphasises that a disaster-resilient city ensures essential services for its residents [12].

Dincer and Ercoşkun [13] investigated the challenges of urban resilience and climate change within the context of advancing technological landscapes. The objective of the research was to develop an urban resilience index that holistically captures the dimensions of physical infrastructure, environmental and climatic factors, and socioeconomic dynamics. Gahi *et al.* [14] developed a fresh index to assess water resources in Burkina Faso, focusing on vulnerability analysis and resilience indicators.

Table 1. Comparison of recent studies on the urban resilience index

Index	Model	Indicator	Identified gaps in research	Reference
-	Trends, simulation model	Power consumption, CO_2 emissions, thermal comfort, and daylight use.	Focuses specifically on architectural approach, not multidimensional (e.g. lack of social, economic indicators).	[9]
Climate Resilience Index (CRI)	Principal component analysis (PCA), weighting	Social capital, access to infra-structure, income diversification, access to resources.	Used mainly at household level, not in an urban context. Does not take into account a broad spectrum of climate impacts (e.g. energy use, green infrastructure).	[10]
Composite National Climate Resilience Index (CNCRI)	Aggregation of composite indicators	Social, economic, infrastructural, environmental and institutional.	International, not local focus (averaged values). Lack of statistical validation (e.g. PCA or clustering).	[11]
Climate Disaster Resilience Index (CDRI)	Aggregation	Social, economic, and infrastructural dimensions	Focus on disasters, not general climate impacts. Does not consider complex interactions between climate and economic systems.	[12]
Urban Resilience Index	0-1 Normalisation, 0-2 sum of index values, Arcgis Pro 2.9 software	Physical infra-structure, environ-mental and climatic factors, socioecon-omic dynamics	Local focus (Ankara), no universal methodological framework. No comprehensive integration of social or economic dimensions .	[13]
SDEWES City Index	Normalisation, aggregation and uncertainty analyses	Urban energy, water and environmental systems performance; urban planning and social welfare	It focuses mainly on technical performance metrics (energy, water, environmental systems), but also includes an underrepresented sixth dimension concerning urban planning and social welfare, which is relevant for city-level sustainability planning.	[15]
Environmental Urban Resilience Index (EURI)	Normalisation, simple summary of indicators	6 environmental and infrastructure indicators	Few indicators used, narrow study area, lack of statistical validation.	[16]

Cleves *et al.* [17] proposed structural and linkage indicators to assess agroecosystem resilience to climate variability. Harwell *et al.* [18] emphasised the importance of indicators and indices in addressing complex scientific questions related to resilience. The SDEWES City Index assesses the sustainability of 18 cities in South East Europe; it is indirectly related to climate resilience. The index measures the performance of urban energy, water and environmental systems and helps to identify cities as pioneering, transitional, transitioning, solution-seeking or challenging. Although the SDEWES Index focuses primarily on technical performance indicators, it also includes a sixth dimension encompassing urban planning and social welfare, which is relevant for city-level sustainability planning. This aspect is often underrepresented in summary descriptions and should be acknowledged when considering the broader implications of urban resilience [15].

A few studies offer insights for the development of a climate resilience index for Hungary. Research by Mohammed *et al.* [19] emphasised the significance of agricultural practices in bolstering resilience to climate change impacts. Pinke and Lövei [20] underscored the vulnerability of Hungarian agriculture to weather extremes such as droughts and proposed landscape adaptation and restoration to enhance resilience. Furthermore, Li *et al.* [21] investigated farmers' perceptions of climate change risks and their adaptive behaviour in Hungary, offering pertinent information for crafting indicators for a climate resilience index. In 2022, Greutter-Gregus [16] discussed the findings of the environmental index for the largest Hungarian cities in both the easternmost and westernmost counties selected based on their population size. In the Hungarian context, Sebestyén *et al.* [22] adapted the SDEWES City Index to assess the sustainability performance of Veszprém and Zalaegerszeg, focusing on urban energy consumption, environmental pressures, and infrastructure efficiency. Their results identified key strengths and deficiencies, particularly related to renewable energy integration and the availability of green spaces. While their research concentrated primarily on technical sustainability indicators, the present study builds upon and expands this approach by integrating social and infrastructural dimensions to provide a more holistic assessment of climate resilience in Hungarian urban areas.

Despite significant progress, current resilience assessments often fail to capture the multifaceted nature of urban systems. Existing indices tend to focus on singular aspects, such as disaster recovery [12] or household-level impacts, and are frequently designed for broad global applications [11], overlooking regional nuances. Hungary presents a unique case for resilience assessment due to its diverse urban landscape, characterised by variations in green infrastructure, energy consumption, and demographic profiles. To address these gaps, the present study introduces the Climate Resilience Index for Town Sustainability (CRITS). This novel framework integrates environmental, social, and infrastructural dimensions into a cohesive, region-specific evaluation. The CRITS index's adaptation to the Hungarian context represents a critical innovation. It explicitly accounts for regional variations, including differences in climate conditions, infrastructure availability, and socioeconomic disparities. This localised approach contrasts with global or regional frameworks that employ generalised indicators, which are less effective in addressing the specific vulnerabilities and strengths of Hungarian cities. By incorporating 41 tailored parameters and normalising the data to ensure comparability, the CRITS index captures the unique challenges faced by Hungarian cities, such as disparities in green infrastructure, renewable energy use, and ageing demographics.

The CRITS index also employs advanced statistical techniques, such as principal component analysis and k-means clustering, to validate the reliability of the indicators and identify meaningful patterns among cities. These methods enable a more robust differentiation of resilience levels across urban areas and provide a basis for targeted policy interventions. In contrast, many existing studies rely on simpler aggregation approaches, which may overlook the complex interdependencies between indicators. The inclusion of clustering allows cities with similar characteristics to share best practices and collaboratively address common challenges, an innovation absent from most comparable indices.

Furthermore, the CRITS index uniquely accounts for the cumulative positive and negative impacts of various factors on resilience. By distinguishing between attributes that enhance or diminish a city's adaptive capacity, the index provides a clearer understanding of areas needing improvement. For instance, indicators such as the availability of green spaces and renewable energy are assigned positive weights, while high energy consumption or limited green infrastructure are considered negative. This dual perspective ensures a balanced and transparent evaluation, which significantly improves upon frameworks that fail to differentiate between beneficial and detrimental factors. The significance of this work lies in its ability to inform actionable policy decisions that can enhance urban climate resilience in Hungary. By identifying the most vulnerable cities to climate change and highlighting specific areas for improvement, the CRITS index provides a practical tool for policymakers. Moreover, its multidimensional framework can be adapted to other regions, making it a significant advancement in the broader field of climate resilience assessment. In summary, the CRITS index not only fills critical scientific gaps but also advances the field by offering a novel, integrated, and context-sensitive approach to urban resilience evaluation.

The reliability of the index developed in this study is supported by the clustering analysis of urban areas. The primary aims of this research are to investigate the following five key hypotheses:

- Hypothesis 1: Cities with higher CRITS scores will show a statistically significant lower frequency and severity of climate-related emergencies compared to cities with lower CRITS scores. Cities with higher CRITS scores will show a statistically significant reduction in the frequency and severity of climate-related emergencies compared to cities with lower CRITS scores.
- Hypothesis 2: The integration of sustainable energy sources and waste management systems, as reflected in the CRITS scores, are positively correlated with the overall climate resilience of urban areas.
- Hypothesis 3: Urban areas with extensive green infrastructure and public amenities, as indicated by the CRITS, will exhibit greater social resilience and improved public health outcomes in response to climate stressors.
- Hypothesis 4: The clustering of cities based on CRITS scores will align with geographic and climatic variations, indicating that local environmental conditions play a critical role in shaping urban resilience.
- Hypothesis 5: The application of principal component analysis and k-means clustering to the CRITS dataset will effectively group Hungarian cities based on their resilience capacity, providing a foundation for targeted policy interventions.

The interdependencies between various urban activities and sectors underlie city resilience, particularly in the realm of energy systems and green infrastructure. This study investigates how the integration of sustainable energy practices and the expansion of green infrastructure can bolster urban resilience. By tackling these pivotal areas, the study highlights the systemic qualities of urban resilience and offers actionable guidance for city-level sustainability planning.

This study provides notable advancements in the measurement and evaluation of climate resilience, with a particular focus on Hungarian cities. The key contributions of this research are summarised as follows:

- This study introduces a novel, multidimensional index known as the Climate Resilience Index for Town Sustainability (CRITS), which assesses and compares the climate resilience of Hungarian municipalities. This index outperforms previous research by incorporating diverse data sources, enabling a more comprehensive evaluation of urban resilience to climate change impacts.
- The CRITS index represents a comprehensive data integration system that incorporates a more extensive array of data sources relative to prior resilience assessment

frameworks. This expanded data integration improves the accuracy and reliability of urban resilience evaluations in the context of climate change.

- The reliability of the CRITS index was validated using k-clustering analysis, effectively categorizing cities into distinct resilience groups based on their unique characteristics. This analysis facilitates tailored policy interventions that address the specific needs and challenges of each resilience group, enhancing the effectiveness of climate change adaptation and mitigation strategies.

METHOD

All relevant statistical indicators were collected from the Hungarian Central Statistical Office [23] and the National Adaptation Geo-Information System [24] for the 18 county capitals and Hungary's capital, Budapest. The relevant data from 205 categories included demographic and settlement data, meteorological indices, and information on building structure and sustainable energy usage. Data from 2022 were utilised in this analysis. The indicators used in the CRITS index focus on urban resilience factors relevant to Hungarian municipalities. While these indicators reflect the specific characteristics of Hungarian cities, similar or additional parameters may be relevant for other urban contexts depending on local conditions and challenges. This flexibility makes the CRITS index adaptable to different regions, providing a versatile tool for assessing urban resilience across diverse environments.

After excluding irrelevant data and obvious redundancies from these 205 parameters, per capita values for all population-related (non-meteorological) features were calculated (Figure 1). A comprehensive correlation matrix was then computed to investigate further interdependencies among the remaining 71 parameters. To reduce redundancy and ensure relevance, a correlation analysis (threshold: $r>0$) was applied, retaining only one parameter per highly correlated group. A total of 41 indicator parameters (factors) were selected for their significance and classified as positive or negative based on their impact on resilience (e.g., green spaces were assigned a positive weight, while high energy consumption was assigned a negative weight; see Table 2). Detailed indicator-impact relationships are presented in the Appendix Tables A1 and A2.

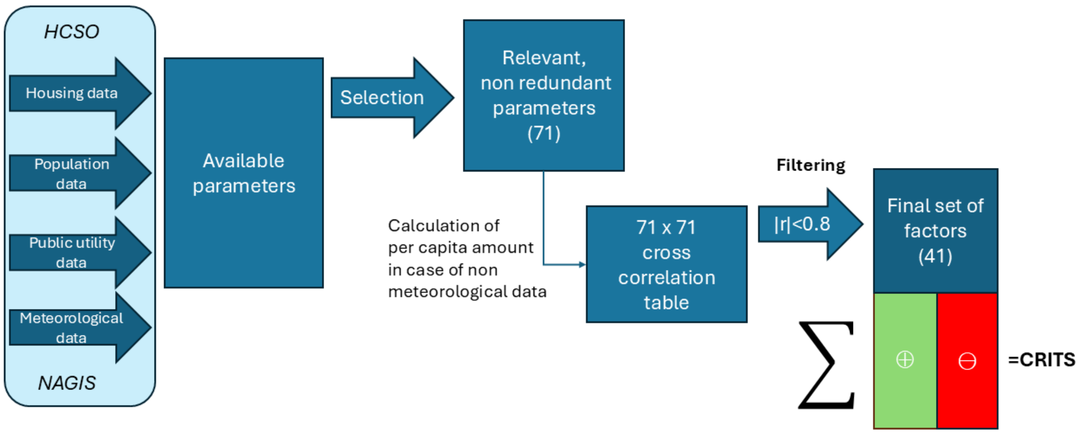

Figure 1. Processing of statistical data to the final selected factors; data sources were HCSO – the Hungarian Central Statistical Office and NAGIS – the National Adaptation Geo-Information System

The CRITS index for each city (I_{city}) is calculated as the signed sum of normalised factor values according to eq. (1). Factor normalisation aimed to ensure comparability across cities with varying scales and units. A scaling parameter ($d = \pm1$) was applied to determine the direction of impact on resilience (positive or negative).

$$I_{city} = \sum_i d \frac{x_i - \overline{x}_i}{\sigma_i} \tag{1}$$

Where x_i denotes the value of *i*-th indicator parameter for the given city (i=1, 2,.., 41), $\overline{x}_i$ – the average value, σ_i – standard deviation, while *d* is a scaling parameter.

Table 2. Applied indicators grouped by their effect on resilience; the indicators' per capita values were used in CRITS, except for meteorological parameters marked with *

Indicators reducing resilience	Positive resilience indicators
Area of the municipality [km^2]	No. of public drinking fountains
Population aged 60 or over [persons]	Length of public water network [km]
Total volume of water supplied [1000 m^3]	Length of public sewerage [km]
Total volume of wastewater discharged to public sewerage [1000 m^3]	Length of low voltage electrical distribution network [km]
Liquid waste transported directly to the wastewater treatment plant [1000 m^3]	Length of gas pipe network [km]
Volume of electricity supplied to households [1000 kWh]	Local government-owned green areas [m^2]
Number of electricity consumers [persons]	Area of playgrounds, exercise tracks, and rest areas [m^2]
Total volume of electricity supplied [1000 kWh]	Length of municipal bicycle paths and combined pedestrian / bicycle paths [km]
Total amount of supplied piped gas [1000 m^3]	Length of municipal pavements [km]
Total number of gas consumers [persons]	No. of vertical load-bearing wall: brick
Regularly cleaned public areas [1000 m^2]	No. of vertical load-bearing wall: adobe
Waste removed from households [t]	No. of dwellings with heat pump systems
Area of paved internal roads in regularly cleaned public spaces [1000 m^2]	No. of dwellings with solar panels
Area of municipal paved roads and public spaces [1000 m^2]	No. of dwellings with solar collector
Area of national public roads [1000 m^2]	
Dwelling stock [piece]	
No. of built dwellings [piece]	
No. of vertical load bearing wall: pre-fabricated	
No. of vertical load bearing wall: concrete	
No. of dwellings with air-conditioning	
Increase in pineal temperature [°C]	
* No. of heat days (hot days)	
*Average rainfall yearly [mm]	
*Global radiation	
* No. of heatwave days	
* No. of frosty days in spring	
* No. of rainfall days exceeding 30 mm	

The CRITS index quantifies a city's climate resilience by summing the normalised values of selected factors, allowing comparisons across various resilience dimensions. Normalising the data ensures comparability between indicators that have diverse units or scales, making the analysis more consistent. The signed sum approach captures both positive and negative impacts of urban attributes on resilience. Beneficial factors—such as the availability of green spaces and renewable energy use—are assigned positive weight. In contrast, detrimental factors – like high energy consumption and limited access to green spaces – receive negative weight. This method simplifies calculations and improves transparency by treating all factors as equally important. However, this unweighted approach might overlook real-world priorities, where certain factors significantly influence resilience outcomes. Future research could explore alternative weighting methods, incorporating stakeholder preferences or expert assessments, to refine the index and align it more closely with specific urban resilience goals.

A potential future enhancement of the CRITS index could involve weighting various factors based on their relative significance in contributing to urban resilience. For example, higher weights could be assigned to renewable energy adoption and green infrastructure due to their direct impact on energy security and environmental sustainability. These weights could be determined through expert assessments or statistical techniques, such as principal component analysis, which identify the most influential factors in resilience evaluation.

The k-means clustering algorithm [25] was used to detect clusters of cities with similar characteristics by taking into account both the final data and a large subset of the initial database. Before conducting clustering, the data were standardised to ensure equal contributions from all variables in the process. The ideal number of clusters was determined using silhouette score analysis. Principal Component Analysis (PCA) was applied for dimensionality reduction [26], resulting in two principal components. These principal components are linear combinations of the original variables, with each component capturing a specific direction of maximum variance in the dataset. The first principal component accounts for the largest variation in the data, while the second captures the next largest variance in a direction orthogonal to the first. Together, these components facilitate the visualisation and interpretation of cluster outcomes in a two-dimensional space. The data analysis and clustering were performed using Python (pandas, scikit-learn packages), a versatile programming language widely used in data science [27].

Cluster analysis offers several benefits for studying the climate resilience of municipalities. First, it groups municipalities with analogous characteristics, enabling the identification of similarities and differences among them. This information can help policymakers' design targeted strategies and interventions tailored to the needs of municipalities facing the most significant climate-related challenges. Furthermore, cluster analysis helps identify municipalities that are particularly vulnerable to significant climate risks, facilitating the effective planning of protective measures against various climate hazards. Lastly, this approach highlights successful climate resilience practices that other municipalities can adopt.

Summing up, the Climate Resilience Index for Town Sustainability considers a range of data, including weather, social, infrastructure, and climate information, to provide a comprehensive assessment of a region's or city's resilience.

RESULTS

This section aims to present the results of the analysis, highlighting similarities and differences between cities and identifying further development opportunities to support targeted policy interventions. Certain cities may be more vulnerable to the impacts of climate change than others, depending on factors such as their geographical location, infrastructure, and population density.

Climate Resilience Index for town sustainability

To enhance the transparency of the CRITS index data, a summary table is provided, showing the raw data for 19 Hungarian urban areas before normalisation. This table offers a clear overview of the values for each indicator, which were later normalised to ensure comparability across the cities. The full dataset, including both raw and normalised values, is available in the Appendix **Table A3**.

Table 3 below presents examples (six cities) of the raw urban-area data from 2022 before normalisation. These data were later processed using standard normalisation techniques, which allowed for comparisons between cities with differing scales and units. The current climate resilience index values for the cities studied reveal substantial variations. These values are highly complex, as the research integrates multiple statistical and meteorological data expressed through environmental, economic, or social indicators.

The CRITS index demonstrated significant efficacy in highlighting and amplifying the differences among the investigated Hungarian cities (**Figure 2**) as scores range from –13 to 20 with a mean of approximately 0 and a standard deviation of 8.64. The majority of the cities on the list exhibit negative values, with Budapest, Székesfehérvár, and Tatabánya demonstrating particularly high negative figures of -12.43, -9.83, and -9.58, respectively. This suggests that these cities are encountering substantial challenges related to the effects of climate change, which are considerably exacerbating living standards or environmental conditions due to decreased resilience.

A positive CRITS score suggests that a city exhibits more advantageous attributes for addressing climate resilience. These include factors in the case of Békéscsaba, such as the large area of local government-owned green areas, the high number of dwellings with solar collectors, and a low population aged 60 or over. In this regard, a city with a greater CRITS score demonstrates decreased vulnerability to climate-related risks and enhanced ability to implement sustainable practices.

Table 3. Examples of raw urban-area data in 2022 before normalisation

Town	Index value	Local government-owned green areas [m^2]	Population aged 60 or over [persons]	Municipal paved roads & public spaces areas [1000 m^2]	Total number of gas consumers [persons]	No. of dwellings with solar panels	Dwelling stocks
Budapest	–12.43	24,130,806	445,287	33,606.5	760,311	34,639	963,103
Győr	–6.54	2,090,736	33,194	4,130.2	54,829	2,977	64,061
Eger	–8.27	1,452,733	16,510	800.2	26,865	744	27,217
Pécs	2.22	10,598,720	47,631	3,103.9	53,612	3,291	74,111
Kecskemét	14.05	2,847,629	36,289	2,010.1	45,710	3,141	54,984
Békéscsaba	19.70	2,280,262	17,672	1,087.7	28,373	2,051	29,966

Conversely, a negative CRITS score, as in the case of Budapest, suggests that a city faces challenges in resilience due to adverse factors such as the low area of local government-owned green areas, large number of dwelling stocks, and low area of playgrounds, exercise tracks, and rest areas. A lower score reflects increased exposure to climate risks, making the city less adaptable to climate changes.

Cities such as Eger, Győr, and Szeged also show notable negative values, signalling areas of concern. For instance, in the case of Győr, unfavourable impacts include high per capita municipal road and public space coverage along with piped gas supply amounts. However, some urban areas, including Békéscsaba, Kecskemét, Nyíregyháza, Zalaegerszeg, and

Szombathely demonstrate positive ratings. In particular, Békéscsaba stands out with a notably high score of 19.70. These scores indicate advantageous environmental or social attributes such as improved standard of living, reduced environmental impact, and overall increased capacity to withstand the impacts of climate change.

The analysis of the CRITS scores highlights the multidimensional nature of urban climate resilience. Cities with higher scores demonstrate the benefits of both environmental assets and well-developed social and infrastructural systems. For instance, the extent of public water networks and the availability of renewable energy infrastructure positively correlate with resilience, as these factors enhance resource distribution efficiency and mitigate the risks posed by extreme climatic events. Conversely, cities with lower scores often face challenges stemming from their urban design and demographic characteristics. As shown in **Table 3**, Budapest's extensive dwelling stocks and limited green areas correspond with the low CRITS score in **Figure 2**, indicating significant urban resilience challenges. These findings suggest that targeted investments in green infrastructure and energy efficiency could significantly bolster the resilience of such urban areas.

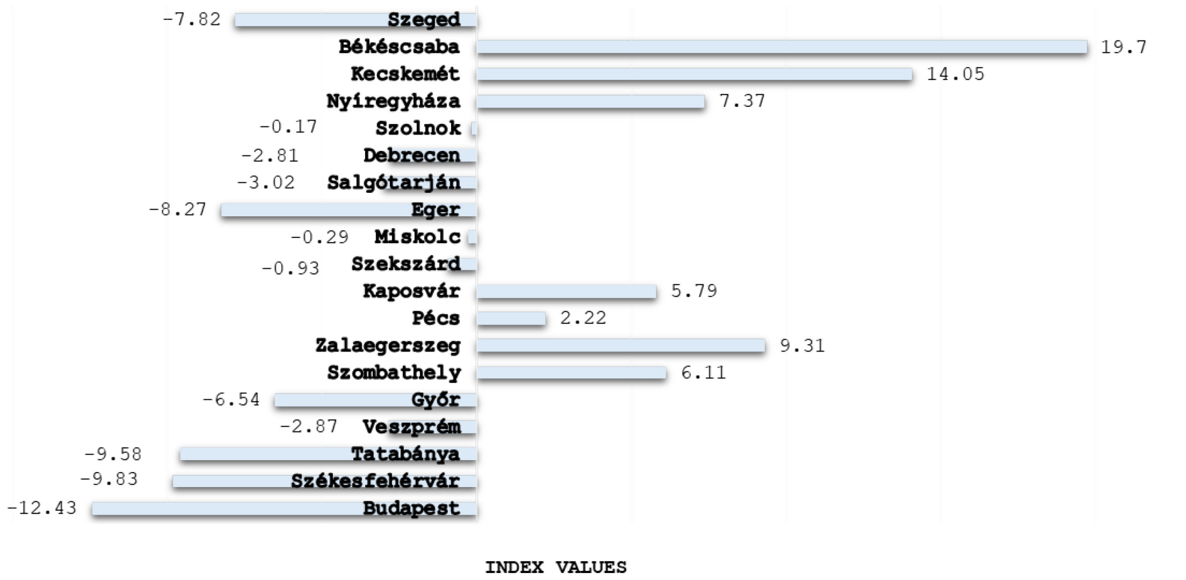

Figure 2. Climate Resilience Index for Town Sustainability

Clustering analyses

Clustering based solely on census or settlement data yielded less satisfactory results compared to the combined dataset, as indicated by lower silhouette scores. This situation suggests that the combined dataset provides a more cohesive and distinct clustering structure, likely because it incorporates a broader range of relevant variables that capture the complexity of the data more effectively. On the other hand, if based only on meteorological data, clustering reflected geographic locations. The best clustering of the entire combined dataset, as shown in **Figure 3**, demonstrated good agreement with the selected dataset, which consists of 41 parameters. The optimal clusters (silhouette score = 0.64) are as follows: 1. Zalaegerszeg and Pécs; 2. Székesfehérvár, Szolnok, Nyíregyháza, and Kecskemét; 3. Eger and Salgótarján; 4. Békéscsaba and Szeged; 5. Budapest, Tatabánya, Győr and Miskolc; 6. Kaposvár and Szekszárd; 7. Veszprém and Szombathely; 8. Debrecen.

Cities in Cluster 1 (Zalaegerszeg and Pécs) benefit from shared strengths like extensive green infrastructure, while those in Cluster 5 (Budapest, Tatabánya, Győr, Miskolc) face common challenges such as high population density and limited renewable energy use. The grouping of cities in Cluster 5 reveals shared challenges, particularly in the form of high population densities and insufficient renewable energy adoption. This result highlights the need for targeted interventions, such as expanding solar panel installations and creating additional green spaces.

The results of the k-means clustering were shown to be robust, as adding or removing a few parameters did not significantly affect the outcomes. In addition, the PCA-based representation confirms the separability of the clusters. The principal component with the highest loading in PCA Component 1 is average annual rainfall, with a weight of 0.97. It is followed by the per capita size of local government-owned green spaces with a weight of 0.005, along with several other factors that exhibit similar loadings. Similarly, meteorological variables, such as precipitation, also show a dominant contribution in PCA Component 2, with a loading of 0.96. Summing up, the clustering reflects similarities of the cities in the multidimensional space of the 41 selected parameters. However, this model does not account for the positive or negative impacts of each index parameter on climate resilience.

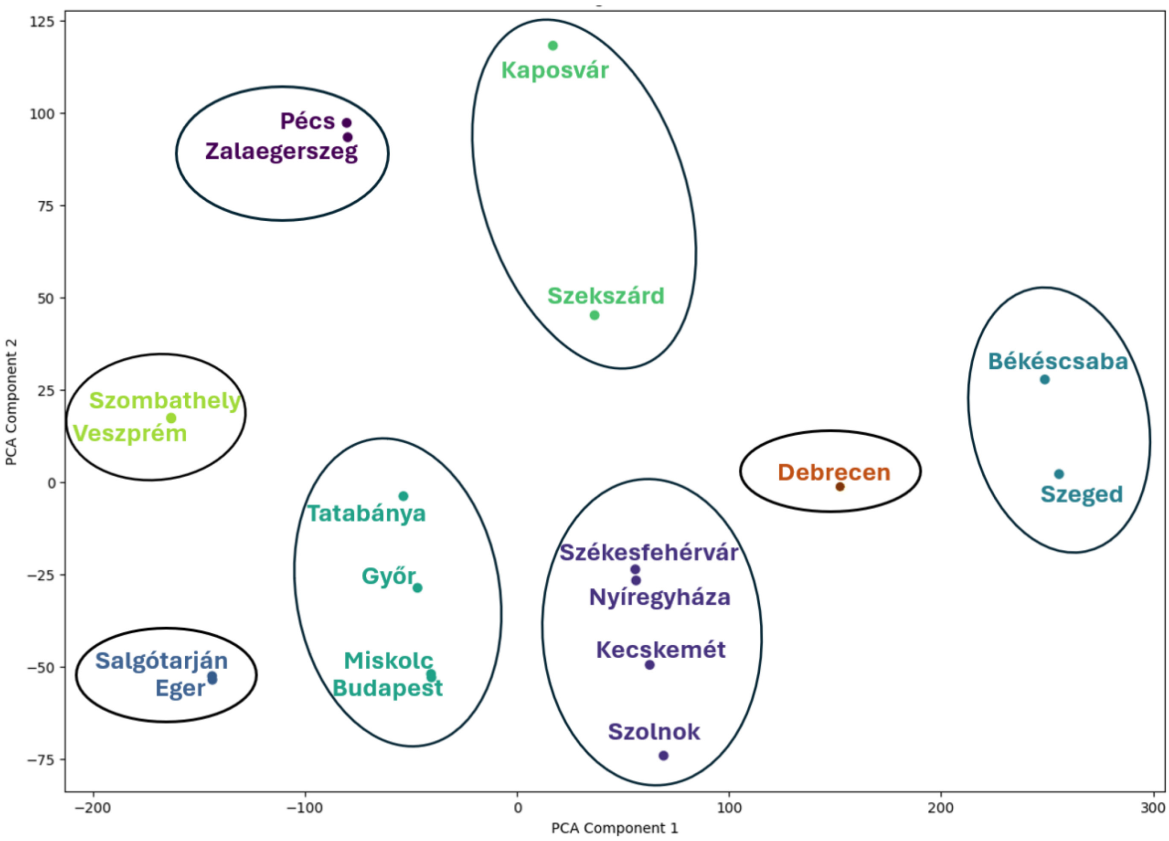

Figure 3. Results of k-means clustering with the optimal 8 clusters for the 18 county capitals and the capital of Hungary

The findings also highlight the physical mechanisms underlying urban resilience. For example, cities with abundant green spaces experience reduced heat absorption and enhanced evaporative cooling. These processes help mitigate the urban heat island phenomenon. Similarly, adopting renewable energy sources reduces dependency on fossil fuels, lowers greenhouse gas emissions, and enhances energy security during extreme weather events. Additionally, clustering patterns reveal the ways in which geographic and climatic factors shape resilience. Municipalities situated in regions with higher average rainfall or temperature extremes tend to face greater challenges, underscoring the need for region-specific adaptation strategies. This spatial variation highlights the importance of tailoring resilience-building measures to local environmental conditions.

Research hypotheses in the light of obtained results

Regarding the first hypothesis, the findings suggest that the high CRITS scores reflect cities' greater resilience to climate change challenges. The results of this analysis support the hypothesis that higher CRITS scores are significantly associated with fewer and less severe climate emergencies, highlighting the importance of urban resilience.

For the second hypothesis, the analysis of CRITS scores shows that integrating sustainable energy sources and efficient waste management systems enhances the climate resilience of urban areas. Cities with higher CRITS scores generally had better indicators for sustainable energy use and waste management, contributing to their increased resilience to climate change challenges. This correlation supports the hypothesis that adopting sustainable practices is crucial for enhancing cities' climate resilience, helping them manage climate stressors and risks more effectively. The adoption of solar panels in cities such as Békéscsaba not only reduces reliance on fossil fuels but also enhances energy security during extreme weather events, serving as a replicable model for other urban areas.

Regarding the third hypothesis, the CRITS index reveals that urban areas with extensive green infrastructure and community facilities demonstrate higher social resilience and improved public health outcomes in response to climate change stressors. Green spaces and community infrastructure, such as parks, playgrounds, and cycle paths, enhance the physical and mental health of city dwellers, reduce the heat island effect, and mitigate the heat island effect, and increase a city's resilience to extreme weather events. In such areas, people are better prepared for the consequences of climate change, as infrastructure fosters community cohesion, protects local ecosystems, and improves access to health services, ultimately enhancing societal resilience.

On the fourth hypothesis, clustering cities based on the CRITS index highlights the significant impact of geographical and climatic differences on urban resilience. The results indicate that cities with similar geographic locations and climate conditions often belong to the same cluster, underscoring the strong influence of local environmental factors on urban resilience. This finding supports the hypothesis that local environmental factors play a crucial role in shaping urban resilience.

The clustering analysis revealed that cities within similar clusters can benefit from exchanging best practices. For example, municipalities with well-developed green infrastructure, such as Zalaegerszeg, could share their strategies for enhancing urban green spaces with cities in Cluster 8, where such elements are lacking. Similarly, localities that have successfully adopted renewable energy could offer valuable insights into scaling sustainable energy systems and strengthening energy resilience in other areas.

Summing up, the CRITS index provides a unique, multidimensional framework that combines environmental, social, and infrastructural indicators, enabling policymakers to prioritise investments in areas with the most significant vulnerabilities, such as Budapest. By adapting the CRITS index methodology to other regions, international collaborations could identify global urban resilience trends, fostering a deeper understanding of climate adaptation strategies.

DISCUSSION

The impacts of natural hazards on infrastructure [28], exacerbated by the effects of climate change, are becoming increasingly severe [29], underscoring the urgent need for resilient energy systems capable of withstanding disruptions [30]. Climate resilience indices [31], such as the Climate Resilience Index [32], are effective tools for mapping the vulnerability of cities and identifying intervention opportunities [33].

Existing research has sought to develop index-based methods for measuring and analysing the resilience of cities in the face of various challenges, from climate change to economic shocks [34]. These indices typically incorporate a range of indicators across different domains, such as infrastructure, governance, and social wellbeing, in order to provide a comprehensive assessment of a city's overall resilience [35]. For example, the City Resilience Index developed by the Rockefeller Foundation and Arup is a prominent example that aims to evaluate the strengths and weaknesses of urban resilience through a framework encompassing four key dimensions [36]: health and wellbeing, economy and society, infrastructure and ecosystems, as well as leadership and strategy [35].

Furthermore, the Climate Disaster Resilience Index has been proposed as a framework to assess the strengths and weaknesses of a city's resilience [37] across key domains such as health and wellbeing, economy and society, infrastructure and ecosystem, as well as leadership and strategy [35]. Building on this, the Urban Resilience and Climate Change Index has taken a more holistic approach by operationalising climate resilience through a framework that integrates urban systems [38], people, and institutions, in line with the definition put forth by the Asian Cities Climate Change Resilience Network [39]. The Asian Cities Climate Change Resilience Network has focused on developing multidimensional indices that integrate the capacity of urban systems, institutions, and people to adapt to the impacts of climate change. Similarly, the Indicators for Monitoring Urban Climate Change Resilience and Adaptation project aimed to develop a comprehensive set of indicators to measure urban climate resilience and track adaptation efforts [34]. Beyond these sector-specific approaches, the broader literature has increasingly recognised the value of indicator-based frameworks for monitoring and evaluating urban climate change resilience and adaptation efforts in a more holistic manner [40]. While these index-based methods represent a significant step forward, they also face some notable limitations. For one, the selection and weighting of indicators can be a subjective process, and the relative importance of different resilience dimensions may vary significantly across contexts.

The CRITS index contributed to the assessment of climate resilience in Hungarian cities by integrating a wide range of complex indicators. The analysis findings indicate that the CRITS index effectively captured differences in climate resilience across Hungarian cities, highlighting substantial variations in their abilities to address the impacts of climate change. By employing principal component analysis and k-means clustering [41], the study successfully distinguished and categorised cities based on their resilience, underscoring the influence of climatic and geographical factors. By employing PCA and clustering, it improved the robustness and interpretability of the index. The results emphasise the strong connection between climate resilience and local environmental conditions. The geographic location of cities fundamentally determines their degree of exposure to the impacts of climate change, particularly extreme weather events [30].

The analysis revealed notable disparities between the studied city clusters. For example, cities such as Zalaegerszeg demonstrated advantageous green infrastructure and higher CRITS ratings, while cities like Budapest or Székesfehérvár exhibited lower scores due to constraints including limited municipal green areas, high-density housing, and elevated energy use [42]. These divergent findings validate the hypothesis that the geographic location and unique attributes of cities are instrumental in moulding their climate adaptation capabilities [43]. Numerous studies have demonstrated that green infrastructure, such as urban parks, green roofs, and forested areas, can mitigate the urban heat island effect, improve air quality, and contribute to enhanced liveability [44].

The CRITS index integrates a wide range of indicators, providing a comprehensive understanding of cities' complex climate resilience [45]. This comprehensive capacity of the CRITS index was further contextualised through a benchmarking analysis with previous studies assessing Hungarian cities. To benchmark the performance of the CRITS index, a comparison was made with two other studies that have assessed urban sustainability or resilience in Hungarian cities. Sebestyén *et al.* [22] applied the SDEWES City Index to Veszprém and Zalaegerszeg. Building on a well-established sustainability index, this approach benefited from a structured, multi-criteria framework covering energy, environmental, and some social aspects. The use of explicit weighting and uncertainty analysis allowed us to tailor the index to local policy priorities (emphasising energy/CO_2, in line with climate action plans) and to test the robustness of results against different comparisons. The method is relatively straightforward to apply to any city with the required data, and results are easy to interpret as radar charts or scores for each dimension. The narrow city sample (only two cities) was a major limitation; it restricts the ability to generalise findings or perform inter-city clustering. The heavy weighting of energy and CO_2 dimensions meant the index was less balanced across sustainability pillars. Some important aspects of resilience (e.g., social equity and climate adaptation measures) were either absent or only indirectly included. Moreover, without statistical validation, the SDEWES index assumed each dimension was independent and important a priori; as noted, this led to redundant indicators and potential biases (favouring smaller cities on per-capita metrics). Thus, while useful for benchmarking technical sustainability, this approach is less suited to capturing holistic resilience to climate shocks. Greutter-Gregus [16] developed an Environmental Urban Resilience Index (EURI), offering a focused look at environmental resilience, which can be advantageous when policymakers seek quick diagnostics of environmental performance. Its simplicity (only 6 indicators) makes it replicable in data-sparse contexts or for rapid assessments. By examining two very different regions (east vs. west), it could shed light on regional disparities in environmental resilience within Hungary. The approach's narrow scope is its chief drawback. With no social or economic indicators, the EURI provides an incomplete picture of urban resilience – essentially treating resilience as a function of environmental factors alone. This omission of dimensions like social vulnerability or economic capacity means the index might misrepresent a city's true resilience (for example, a city with robust infrastructure but high social inequality might score well on EURI but actually be less resilient to crises). The small number of indicators also raises concerns about indicator sufficiency and weighting: each of the 6 inputs carries a lot of weight in the outcome, and any measurement error could swing the results significantly. Finally, the study's limited geographic coverage (only 8 cities in two counties) means its methodology and findings were highly case-specific. There was no attempt to validate the index via PCA or other means, so the reliability of the chosen indicators in measuring "resilience" remained untested.

The CRITS index expands on these previous approaches by evaluating 19 Hungarian cities using a robust set of 41 indicators across environmental, infrastructural, and social dimensions. In addition to offering a broader geographical scope – including cities like Pécs – it introduces statistical validation and clustering analysis, enabling both in-depth city-level assessment and cross-city comparisons. This integrated framework allows for the identification of city-specific vulnerabilities and adaptive capacities, offering a more holistic and actionable perspective on urban resilience planning in Hungary. The index results indicate that urban centres prioritising sustainable energy [46], efficient waste management, and extensive green infrastructure demonstrate greater resilience to climate stressors [47]. For instance, Békéscsaba's high score is linked to its substantial municipal green spaces, widespread solar panel usage, and a relatively low proportion of elderly residents [48]. Conversely, Budapest's negative score reflects a deficiency in green areas, a high density of dwellings, and intense energy consumption [49]. Integrating renewable energy sources, such as solar and wind power, significantly enhances urban energy independence while reducing dependence on fossil fuel resources [50].

According to the CRITS index findings, the study recognised numerous prospective intervention strategies to bolster urban resilience [51]. In municipalities with reduced resilience [52], cultivating green infrastructure is paramount, as it alleviates urban heat island impacts, betters air quality, and elevates overall liveability [53]. Concurrently, integrating renewable energy sources [54], implementing energy efficiency interventions, and developing climate-adaptable infrastructure are equally vital [55]. Moreover, cities facing comparable challenges could gain from exchanging best practices, such as approaches for expanding green spaces or advancing renewable energy adoption [56]. In conclusion, the analysis supports [57] the hypothesis that climate resilience is not solely a function of infrastructure and environmental conditions but also the result of complex interrelations between social and economic factors [58]. The findings provide a basis for designing targeted policy interventions that address the unique challenges and needs of individual cities [59]. These measures could significantly enhance urban climate adaptation capacities in the long term, contributing to more sustainable and liveable urban environments.

CONCLUSIONS

This study introduces the Climate Resilience Index for Town Sustainability, a multidimensional framework designed to evaluate urban climate resilience in Hungarian cities. By integrating environmental, social, and infrastructural dimensions, the index addresses critical gaps in existing resilience assessments, providing a robust, region-specific tool for assessing urban disparities and vulnerabilities. Stronger resilience is linked to green infrastructure, renewable energy use, and sustainable practices, as exemplified by Békéscsaba. In contrast, challenges such as limited green spaces and high energy consumption affect cities like Budapest. The index advances resilience research by combining comprehensive datasets with advanced statistical techniques, including principal component analysis and k-means clustering, to uncover actionable patterns and support targeted interventions. Its regional adaptability and focus on both positive and negative resilience factors make it a valuable tool for policymakers.

Further research offers significant opportunities to enhance and apply this index, enabling more profound insights into the relationship between urbanisation and climate resilience. Expanding the index with additional indicators, such as income inequality, health infrastructure, and workplace resilience, would enable more nuanced analyses and broaden the scope of its application. Refining the weighting methods using dynamic, expert-informed, or statistical approaches could improve the representation of indicator significance across diverse urban contexts. Incorporating temporal considerations would allow the index to capture long-term trends and track resilience evolution instead of providing a static assessment. Extending the application of the index to other regions or countries would increase its global relevance and strengthen its role in supporting international climate adaptation policies. Validating the index through real-world climate event analyses would further reinforce its practical reliability. An interdisciplinary approach that integrates insights from social sciences, environmental studies, and urban research would deepen the understanding of urban resilience and promote sustainable development worldwide.

NOMENCLATURE

I	CRITS index value according to eq. (1)
d	sign of the impact
σ	standard deviation
CRITS	Climate Resilience Index for Town Sustainability
IPCC	Intergovernmental Panel on Climate Change
IPCC WGIII	Intergovernmental Panel on Climate Change, Working Group III

REFERENCES

1. IPCC, "AR6 Synthesis Report: Climate Change 2023," 2023. https://www.ipcc.ch/report/sixth-assessment-report-cycle/ [Accessed: 03-April-2025].
2. S. Tyler and M. Moench, "A framework for urban climate resilience," *Clim Dev*, vol. 4, no. 4, pp. 311–326, Oct. 2012, https://doi.org/10.1080/17565529.2012.745389.
3. D. R. Nelson, "Adaptation and resilience: responding to a changing climate," *WIREs Climate Change*, vol. 2, no. 1, pp. 113–120, Jan. 2011, https://doi.org/10.1002/wcc.91.
4. G. Sarma and A. Zabaniotou, "Understanding Vulnerabilities of Renewable Energy Systems For Building Their Resilience to Climate Change Hazards: Key Concepts And Assessment Approaches," *Renewable Energy and Environmental Sustainability*, vol. 6, p. 35, Oct. 2021, https://doi.org/10.1051/rees/2021035.
5. R. Leichenko, "Climate change and urban resilience," *Curr Opin Environ Sustain*, vol. 3, no. 3, pp. 164–168, May 2011, https://doi.org/10.1016/j.cosust.2010.12.014.
6. A. Sharifi and Y. Yamagata, "Urban Resilience Assessment: Multiple Dimensions, Criteria, and Indicators," 2016, pp. 259–276, https://doi.org/10.1007/978-3-319-39812-9_13.
7. M. González-Pleiter *et al.*, "Fibers spreading worldwide: Microplastics and other anthropogenic litter in an Arctic freshwater lake," *Science of The Total Environment*, vol. 722, p. 137904, Jun. 2020, https://doi.org/10.1016/j.scitotenv.2020.137904.
8. P. Kumar, "Climate Change and Cities: Challenges Ahead," *Frontiers in Sustainable Cities*, vol. 3, Feb. 2021, https://doi.org/10.3389/frsc.2021.645613.
9. A. H. Chohan, J. Awad, M. A. Ismail, and M. S. Arar, "Integrating Technology and Heritage Design for Climate Resilient Courtyard House in Arid Region," *Civil Engineering Journal*, vol. 10, no. 3, pp. 928–952, Mar. 2024, https://doi.org/10.28991/CEJ-2024-010-03-018.
10. M. Asmamaw, S. T. Mereta, and A. Ambelu, "Exploring households' resilience to climate change-induced shocks using Climate Resilience Index in Dinki watershed, central highlands of Ethiopia," *PLoS One*, vol. 14, no. 7, p. e0219393, Jul. 2019, https://doi.org/10.1371/journal.pone.0219393.
11. D. Sono, Y. Wei, and Y. Jin, "Assessing the Climate Resilience of Sub-Saharan Africa (SSA): A Metric-Based Approach," *Land (Basel)*, vol. 10, no. 11, p. 1205, Nov. 2021, https://doi.org/10.3390/land10111205.
12. A. Mukherjee, Md. Faisal, and M. K. Saha, "Measuring Resilience of Urban Slum to Climate Induced Disasters: A Study on Barishal City Corporation, Bangladesh," *International Journal of Disaster Management*, vol. 3, no. 2, pp. 34–47, Dec. 2020, https://doi.org/10.24815/ijdm.v3i2.17815.
13. Ş. E. Dincer and Ö. Y. Ercoşkun, "Urban Resilience Index Study on Ankara Metropolitan Area," *Iconarp International J. of Architecture and Planning*, Dec. 2024, https://doi.org/10.15320/ICONARP.2024.293.
14. N. Gahi, K. Dongo, and M. Badolo, "Using a New Approach to Design Innovative Tools for Monitoring and Evaluating Water Policy of Burkina Faso in Response to Climate Risks," *Climate*, vol. 3, no. 4, pp. 1057–1078, Dec. 2015, https://doi.org/10.3390/cli3041057.
15. Ş. Kılkış, "Issue 4, 1120518 Journal of Sustainable Development of Energy, Water and Environment Systems ISSN," vol. 12, no. 4, p. 1120518, 2024, https://doi.org/10.13044/j.sdewes.d12.0518.
16. Greutter-Gregus É., "Environmental Index and Environmental City Resilience Index calculation for Four Settlements in Szabolcs-Szatmár-Bereg County and Four in Győr-Moson-Sopron County.," *International Journal of Engineering and Management Sciences (IJEMS)*, vol. 7, no. 4, 2022, https://doi.org/10.21791/IJEMS.2022.4.2.

17. A. Cleves, E. Youkhana, and J. Toro, “A Method to Assess Agroecosystem Resilience to Climate Variability,” *Sustainability*, vol. 14, no. 14, p. 8588, Jul. 2022, https://doi.org/10.3390/su14148588.
18. L. C. Harwell, D. N. Vivian, M. D. McLaughlin, and S. F. Hafner, “Scientific Data Management in the Age of Big Data: An Approach Supporting a Resilience Index Development Effort,” *Front Environ Sci*, vol. 7, Jun. 2019, https://doi.org/10.3389/fenvs.2019.00072.
19. S. Mohammed *et al.*, “Assessing the impacts of agricultural drought (SPI/SPEI) on maize and wheat yields across Hungary,” *Sci Rep*, vol. 12, no. 1, p. 8838, May 2022, https://doi.org/10.1038/s41598-022-12799-w.
20. Z. Pinke and G. L. Lövei, “Increasing temperature cuts back crop yields in Hungary over the last 90 years,” *Glob Chang Biol*, vol. 23, no. 12, pp. 5426–5435, Dec. 2017, https://doi.org/10.1111/gcb.13808.
21. J. Li, “Wastes could be resources and cities could be mines,” *Waste Management & Research: The Journal for a Sustainable Circular Economy*, vol. 33, no. 4, pp. 301–302, Apr. 2015, https://doi.org/10.1177/0734242X15581268.
22. V. Sebestyén, V. Somogyi, S. Szőke, and A. Utasi, “Adapting the SDEWES Index to Two Hungarian Cities,” *Hungarian Journal of Industry and Chemistry*, vol. 45, no. 1, pp. 49–59, Oct. 2017, https://doi.org/10.1515/hjic-2017-0008.
23. “Hungarian Central Statistical Office,” May 09, 2024. https://statinfo.ksh.hu/Statinfo/themeSelector.jsp?lang=hu [Accessed: 09-May-2024].
24. “National Adaptation Geo-Information System,” May 09, 2024. https://map.mbfsz.gov.hu/nater/ [Accessed: 09-May-2024].
25. Douglas. Steinley, “K-means clustering: A half-century synthesis,” *British Journal of Mathematical and Statistical Psychology*, vol. 59, no. 1, pp. 1–34, May 2006, https://doi.org/10.1348/000711005X48266.
26. I. T. Jolliffe and J. Cadima, “Principal component analysis: a review and recent developments,” *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 374, no. 2065, p. 20150202, Apr. 2016, https://doi.org/10.1098/rsta.2015.0202.
27. F. Pedregosa *et al.*, “Scikit-learn: Machine Learning in Python,” Jan. 2012, [Online]. Available: http://arxiv.org/abs/1201.0490. [Accessed: 03-April-2025].
28. B. Rathnayaka *et al.*, “Identifying and prioritizing climate change adaptation measures in the context of electricity, transportation and water infrastructure: A case study,” *International Journal of Disaster Risk Reduction*, vol. 99, p. 104093, Dec. 2023, https://doi.org/10.1016/j.ijdrr.2023.104093.
29. S. S. Ottenburger *et al.*, “Sustainable urban transformations based on integrated microgrid designs,” *Nat Sustain*, vol. 7, no. 8, pp. 1067–1079, Jul. 2024, https://doi.org/10.1038/s41893-024-01395-7.
30. G. Dharmarathne, A. O. Waduge, M. Bogahawaththa, U. Rathnayake, and D. P. P. Meddage, “Adapting cities to the surge: A comprehensive review of climate-induced urban flooding,” *Results in Engineering*, vol. 22, p. 102123, Jun. 2024, https://doi.org/10.1016/j.rineng.2024.102123.
31. J. Z. Farkas, E. Hoyk, and J. Rakonczai, “Geographical analysis of climate vulnerability at a regional scale: the case of the Southern Great Plain in Hungary,” *Hungarian Geographical Bulletin*, vol. 66, no. 2, pp. 129–144, Jul. 2017, https://doi.org/10.15201/hungeobull.66.2.3.
32. D. Feldmeyer, D. Wilden, A. Jamshed, and J. Birkmann, “Regional climate resilience index: A novel multimethod comparative approach for indicator development, empirical validation and implementation,” *Ecol Indic*, vol. 119, p. 106861, Dec. 2020, https://doi.org/10.1016/j.ecolind.2020.106861.

33. B. Rathnayaka *et al.*, "A unified framework for evaluating the resilience of critical infrastructure: Delphi survey approach," *International Journal of Disaster Risk Reduction*, vol. 110, p. 104598, Aug. 2024, https://doi.org/10.1016/j.ijdrr.2024.104598.
34. D. Feldmeyer *et al.*, "Indicators for Monitoring Urban Climate Change Resilience and Adaptation," *Sustainability*, vol. 11, no. 10, p. 2931, May 2019, https://doi.org/10.3390/su11102931.
35. G. Oriangi, Y. Bamutaze, P. I. Mukwaya, P. Musali, G. Di Baldassarre, and P. Pilesjö, "Testing the Proposed Municipality Resilience Index to Climate Change Shocks and Stresses in Mbale Municipality in Eastern Uganda," *Am J Clim Change*, vol. 08, no. 04, pp. 520–543, 2019, https://doi.org/10.4236/ajcc.2019.84028.
36. A. Galderisi, G. Limongi, and K.-D. Salata, "Strengths and weaknesses of the 100 Resilient Cities Initiative in Southern Europe: Rome and Athens' experiences," *City, Territory and Architecture*, vol. 7, no. 1, p. 16, Dec. 2020, https://doi.org/10.1186/s40410-020-00123-w.
37. H. Tariq, C. Pathirage, and T. Fernando, "Measuring community disaster resilience at local levels: An adaptable resilience framework," *International Journal of Disaster Risk Reduction*, vol. 62, p. 102358, Aug. 2021, https://doi.org/10.1016/j.ijdrr.2021.102358.
38. A. Urquiza *et al.*, "An Integrated Framework to Streamline Resilience in the Context of Urban Climate Risk Assessment," *Earths Future*, vol. 9, no. 9, Sep. 2021, https://doi.org/10.1029/2020EF001508.
39. A. Jamali, M. Robati, H. Nikoomaram, F. Farsad, and H. Aghamohammadi, "Urban Resilience and Climate Change: Developing a Multidimensional Index to Adapt against Climate Change in the Iranian Capital City of Tehran," *Urban Science*, vol. 7, no. 1, p. 7, Jan. 2023, https://doi.org/10.3390/urbansci7010007.
40. A. Sharifi and Y. Yamagata, "Principles and criteria for assessing urban energy resilience: A literature review," *Renewable and Sustainable Energy Reviews*, vol. 60, pp. 1654–1677, Jul. 2016, https://doi.org/10.1016/j.rser.2016.03.028.
41. I. R. Orimoloye, S. P. Mazinyo, A. M. Kalumba, O. Y. Ekundayo, and W. Nel, "Implications of climate variability and change on urban and human health: A review," *Cities*, vol. 91, pp. 213–223, Aug. 2019, https://doi.org/10.1016/j.cities.2019.01.009.
42. R. Aslanoğlu *et al.*, "Ten questions concerning the role of urban greenery in shaping the future of urban areas," *Build Environ*, vol. 267, p. 112154, Jan. 2025, https://doi.org/10.1016/j.buildenv.2024.112154.
43. P. Kumar *et al.*, "Urban heat mitigation by green and blue infrastructure: Drivers, effectiveness, and future needs," *The Innovation*, vol. 5, no. 2, p. 100588, Mar. 2024, https://doi.org/10.1016/j.xinn.2024.100588.
44. Ugochukwu Kanayo Ashinze, Blessing Aibhamen Edeigba, Aniekan Akpan Umoh, Preye Winston Biu, and Andrew Ifesinachi Daraojimba, "Urban green infrastructure and its role in sustainable cities: A comprehensive review," *World Journal of Advanced Research and Reviews*, vol. 21, no. 2, pp. 928–936, Feb. 2024, https://doi.org/10.30574/wjarr.2024.21.2.0519.
45. S. M. Rezvani, M. J. Falcão, D. Komljenovic, and N. M. de Almeida, "A Systematic Literature Review on Urban Resilience Enabled with Asset and Disaster Risk Management Approaches and GIS-Based Decision Support Tools," *Applied Sciences*, vol. 13, no. 4, p. 2223, Feb. 2023, https://doi.org/10.3390/app13042223.
46. Y. Lv and M. N. I. Sarker, "Integrative approaches to urban resilience: Evaluating the efficacy of resilience strategies in mitigating climate change vulnerabilities," *Heliyon*, vol. 10, no. 6, p. e28191, Mar. 2024, https://doi.org/10.1016/j.heliyon.2024.e28191.
47. R. Kumar, "Evaluating the Impact of Green Infrastructure on Urban Ecosystems: A Case Study Approach," *International Journal for Research Publication and Seminar*, vol. 15, no. 3, pp. 282–288, Sep. 2024, https://doi.org/10.36676/jrps.v15.i3.1495.

48. M. Farghali *et al.*, "Social, environmental, and economic consequences of integrating renewable energies in the electricity sector: a review," *Environ Chem Lett*, vol. 21, no. 3, pp. 1381–1418, Jun. 2023, https://doi.org/10.1007/s10311-023-01587-1.
49. L. S. Paraschiv and S. Paraschiv, "Contribution of renewable energy (hydro, wind, solar and biomass) to decarbonization and transformation of the electricity generation sector for sustainable development," *Energy Reports*, vol. 9, pp. 535–544, Sep. 2023, https://doi.org/10.1016/j.egyr.2023.07.024.
50. S. Algarni, V. Tirth, T. Alqahtani, S. Alshehery, and P. Kshirsagar, "Contribution of renewable energy sources to the environmental impacts and economic benefits for sustainable development," *Sustainable Energy Technologies and Assessments*, vol. 56, p. 103098, Mar. 2023, https://doi.org/10.1016/j.seta.2023.103098.
51. V. M. Jayasooriya, A. W. M. Ng, S. Muthukumaran, and B. J. C. Perera, "Green infrastructure practices for improvement of urban air quality," *Urban For Urban Green*, vol. 21, pp. 34–47, Jan. 2017, https://doi.org/10.1016/j.ufug.2016.11.007.
52. A. M. M. Irfeey, H.-W. Chau, M. M. F. Sumaiya, C. Y. Wai, N. Muttil, and E. Jamei, "Sustainable Mitigation Strategies for Urban Heat Island Effects in Urban Areas," *Sustainability*, vol. 15, no. 14, p. 10767, Jul. 2023, https://doi.org/10.3390/su151410767.
53. S. N. Sharma, "Nature Based Solutions to Prevent Urban Flooding," 2024, https://doi.org/10.5281/zenodo.10651295. [Accessed: 03-April-2025]
54. L. Chen *et al.*, "Green building practices to integrate renewable energy in the construction sector: a review," *Environ Chem Lett*, vol. 22, no. 2, pp. 751–784, Apr. 2024, https://doi.org/10.1007/s10311-023-01675-2.
55. F. Oluwadamilare Usman, E. Chigozie Ani, W. Ebirim, D. J. Portillo Montero, K. A. Olu-lawal, and N. Ninduwezuor-Ehiobu, "INTEGRATING RENEWABLE ENERGY SOLUTIONS IN THE MANUFACTURING INDUSTRY: CHALLENGES AND OPPORTUNITIES: A REVIEW," *Engineering Science & Technology Journal*, vol. 5, no. 3, pp. 674–703, Mar. 2024, https://doi.org/10.51594/estj.v5i3.865.
56. A. G. Olabi *et al.*, "Renewable energy systems: Comparisons, challenges and barriers, sustainability indicators, and the contribution to UN sustainable development goals," *International Journal of Thermofluids*, vol. 20, p. 100498, Nov. 2023, https://doi.org/10.1016/j.ijft.2023.100498.
57. A. Jurgilevich *et al.*, "Factors influencing vulnerability to climate change-related health impacts in cities – A conceptual framework," *Environ Int*, vol. 173, p. 107837, Mar. 2023, https://doi.org/10.1016/j.envint.2023.107837.
58. M. M. Al-Humaiqani and S. G. Al-Ghamdi, "The built environment resilience qualities to climate change impact: Concepts, frameworks, and directions for future research," *Sustain Cities Soc*, vol. 80, p. 103797, May 2022, https://doi.org/10.1016/j.scs.2022.103797.
59. S. E. Bibri, J. Krogstie, and M. Kärrholm, "Compact city planning and development: Emerging practices and strategies for achieving the goals of sustainability," *Developments in the Built Environment*, vol. 4, p. 100021, Nov. 2020, https://doi.org/10.1016/j.dibe.2020.100021.

APPENDIX

Table A1. Presentation of indicator-impact relationships, part 1; HCSO – Hungarian Central Statistical Office, positive impact denoted by +1 and negative impact by –1

Indicator	Reference	Impact	Explanation
Area of the municipality [km^2]	HCSO	–1	Larger areas – more infrastructure maintenance, increased vulnerability to resource demand and climate change impacts.
Population aged 60 or over [persons]	HCSO	–1	The older population is more vulnerable to extreme weather events (e.g. heat waves), reducing urban resilience.
Total volume of water supplied [1000 m^3]	HCSO	–1	High water consumption increases energy use and stress on water supply systems.
Wastewater discharged to public sewerage [1000 m^3]	HCSO	–1	Discharging large volumes of wastewater requires more energy and infrastructure, increasing the vulnerability of resources.
Liquid waste transported to wastewater treatment [1000 m^3]	HCSO	–1	Large quantities of waste transported imply increased logistical and energy requirements.
Electricity supplied to households [1000 kWh]	HCSO	–1	High energy consumption means greater dependence on fossil fuels, reducing sustainability.
No. of electricity consumers	HCSO	–1	A larger consumer base increases the load and vulnerability of the energy network.
Total electricity supplied [1000 kWh]	HCSO	–1	High electricity consumption – increased environmental pressures, especially when energy comes from fossil fuels. This increases carbon emissions, increases energy dependence and can overload the energy grid.
Total amount of supplied piped gas [1000 m^3]	HCSO	–1	Natural gas consumption increases dependence on fossil energy, reducing climate resilience.
No. of gas consumers	HCSO	–1	A large number of gas consumers – increased demand for fossil fuels, increased GHG emissions and energy dependence.
Regularly cleaned public areas [1000 m^2]	HCSO	–1	Maintaining regularly cleaned public areas requires significant energy, water and labour. Increases the urban heat island effect.
Waste removed from households [t]	HCSO	–1	Removing large amounts of household waste increases energy use and carbon emissions, especially when done with inefficient waste management systems. This contributes to GHG emissions and wastes resources.
Area of paved roads in regularly cleaned public spaces [1000 m^2]	HCSO	–1	Large areas of paved roads reduce natural drainage capacity, increasing the risk of flooding. Maintaining such areas requires additional energy and resources.
Area of municipal paved roads and public spaces [1000 m^2]	HCSO	–1	Large areas of paved roads and public spaces contribute to the urban heat island effect, which increases the impact of heat waves.
Area of national public roads [1000 m^2]	HCSO	–1	Large areas of paved roads contribute to the urban heat island effect, which increases the impact of heat waves
Dwelling stock	HCSO	–1	More buildings mean higher maintenance needs, which can put pressure on infrastructure during climate extremes.
No. of built dwellings	HCSO	–1	A large number of built dwellings increases

Indicator	Reference	Impact	Explanation
			urbanisation, leading to more energy and resource use, especially during the construction process. Paved areas reduce natural ground cover, exacerbating drainage problems and urban heat island effect.
No. of vertical load bearing wall: pre-fabricated	HCSO	−1	Pre-fabricated frame structures often have low thermal insulation properties, which increases the energy consumption of buildings, especially for heating and cooling.
No. of vertical load bearing wall: concrete	HCSO	−1	Concrete masonry load-bearing structures have a negative impact on urban resilience by increasing energy consumption and carbon emissions while reducing the resilience of buildings to the effects of climate change.
No. of dwellings with air conditioning	HCSO	−1	It results in increased energy consumption, putting strain on the energy grid, especially during heat waves.

Table A2. Presentation of indicator-impact relationships, part 2; HCSO – Hungarian Central Statistical Office, NAGiS – National Adaptation Geo-information System, positive impact denoted by +1 and negative impact by −1

Indicator	Reference	Impact	Explanation
Increase in pineal temperature [°C]	NAGiS	−1	Higher temperatures increase energy demand and health risks.
No. of hot days	NAGiS	−1	More frequent heat waves have direct health and economic impacts.
*Average rainfall yearly [mm]	NAGiS	−1	High annual rainfall can increase the risk of infrastructure overloading and flooding in urban environments (paved surfaces impede natural drainage).
*Global radiation	NAGiS	−1	High global radiation increases the intensity of the urban heat island effect, which can lead to extreme temperature conditions and higher energy demand for cooling.
*No. of heatwave days	NAGiS	−1	More heatwave days have health and economic impacts, particularly on vulnerable populations, e.g., elderly. Risk of energy network overload and increased cooling demand.
*No. of frosty days in spring	NAGiS	−1	Frosty days in spring damage agriculture and vegetation, increase energy use for heating and cause economic losses.
*No. of rainfall days exceeding 30 mm	NAGiS	−1	Heavy rainfall increases the risk of flash floods that damage infrastructure and transport systems. This leads to higher maintenance costs and lower resilience.
No. of public drinking fountains	HCSO	−1	Improve public access to clean water, especially during extreme heat waves, reducing heat stress.
Length of public water network [km]	HCSO	+1	An extensive water network improves water supply reliability, an important climate adaptation consideration.
Length of public sewerage [km]	HCSO	+1	Better sanitation networks reduce the risk of flooding and pollution.
Length of low voltage electrical distribution network [km]	HCSO	+1	An extensive low-voltage electrical network increases the efficiency of energy distribution and improves access to a reliable energy supply (vital during climate change emergencies, when electricity demand increases).
Length of gas pipe network [km]	HCSO	+1	A well-developed gas pipeline network ensures efficient distribution of energy resources and reduces transport losses, improves energy-supply reliability in the short term.
Local gov.-owned green areas [m^2]	HCSO	+1	Green spaces reduce urban heat island effects, improve air quality and enhance ecosystem services.

Indicator	Reference	Impact	Explanation
Area of playgrounds, exercise tracks, and rest areas [m^2]	HCSO	+1	Playgrounds, sports fields and recreational areas increase the green infrastructure of cities, reducing the urban heat island effect, improving air quality and promoting the physical and mental health of the population.
Length of bicycle & walking paths [km]	HCSO	+1	Provide sustainable transport options, reducing emissions from the transport sector.
Length of municipal pavements [km]	HCSO	+1	Improving pedestrian transport infrastructure reduces the use of fossil fuels.
No. of vertical load-bearing walls: brick	HCSO	+1	Load-bearing structures with brick masonry provide better thermal insulation, thus reducing energy consumption, especially heating and cooling demands.
No. of vertical load-bearing walls: adobe	HCSO	+1	Load-bearing structures with adobe masonry provide good thermal insulation and are highly energy efficient, especially in dry, hot climates. Adobe, as a natural material, contributes to environmental sustainability.
No. of dwellings with heat pumps	HCSO	+1	Energy-efficient heating systems reduce energy consumption and carbon emissions.
No. of dwellings with solar panels	HCSO	+1	Increase the share of electricity from renewable energy sources, reducing dependence on fossil energy.
No. of dwellings with solar collector	HCSO	+1	Homes with solar panels use solar energy for heating and hot water; contribute to sustainability and urban resilience by promoting renewable energy use, reducing energy costs and increasing energy independence from climate change.

Table A3. Examples of raw urban area data in 2022 before normalisation

Town	Local government-owned green areas [m^2]	Population aged 60 or over [persons]	Area of municipal paved roads & public spaces [1000 m^2]	No. of gas consumers [persons]	No. of dwellings with solar panels	Dwelling stock
Budapest	24,130,806	445,287	33,606.5	760,311	34,639	963,103
Székesfehérvár	4,331,597	27,541	2,380.5	42,782	2,297	48,340
Tatabánya	1,706,519	17,130	1,290.8	6,024	611	31,453
Veszprém	921,760	15,466	1,194.1	24,254	1,333	27,643
Győr	2,090,736	33,194	4,130.2	54,829	2,977	64,061
Szombathely	1,387,675	21,557	1,471.2	32,345	1,659	36,427
Zalaegerszeg	2,081,453	17,081	1,722.1	26,581	1,039	27,908
Pécs	10,598,720	47,631	3,103.9	53,612	3,291	74,111
Kaposvár	1,500,971	18,298	982.2	27,037	960	30,757
Szekszárd	473,524	9,447	807.3	9,167	679	15,950
Miskolc	3,501,630	46,936	2,475.7	68,080	2,106	79,052
Eger	1,452,733	16,510	800.2	26,865	744	27,217
Salgótarján	1,220,515	9,774	708.1	11,000	218	18,056
Debrecen	1,765,167	67,933	2,980.2	74,284	5,188	100,040
Szolnok	1,500,379	21,635	1,177.6	30,636	1,528	35,912
Nyíregyháza	1,902,103	38,605	1,541.3	45,589	2,466	53,710
Kecskemét	2,847,629	36,289	2,010.1	45,710	3,141	54,984
Békéscsaba	2,280,262	17,672	1,087.7	28,373	2,051	29,966
Szeged	3,771,081	53,577	2,693.4	80,949	4,260	88,416

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