Extra resilience through smart solutions based on nature in Bucharest

Isabelle COICIU,
University of Bucharest, Bucharest, Romania
isabelle.coiciu@s.unibuc.ro

Ioan Florin VOICU,
ING Tech, Bucharest, Romania
ioan-florin.voicu@ing.com

Ioannis APOSTOLIDIS,
University of Bucharest, Bucharest, Romania
ioannis.apostolidis@s.unibuc.ro

Daniel Constantin DIACONU,
Dr., Interdisciplinary Center for Advanced Studies (CISA-ICUB), University of Bucharest,Romania
daniel.diaconu@unibuc.ro

Abstract

The paper aims to assess how nature-based solutions and smart technologies can contribute to increasing climate resilience in Bucharest. This is a city under increasing pressure from climate change, intense urbanization, and a lack of green infrastructure. The research is based on current concepts of climate resilience and sustainable urban planning, which promote the transition to green, resilient, and digitalized cities. The methodological approach integrates GIS spatial analysis by analyzing and processing key meteorological parameters, air temperature, and precipitation from nearly 50 amateur weather stations, with free access to this data throughout the county and municipality. At the same time, surveys on population perception and climate modeling based on machine learning (AutoML) are used, utilizing official and private meteorological data to estimate temperature trends and urban vulnerabilities in different climate scenarios (SSP). The results indicate a steady increase in average temperatures of up to +2°C by 2060, confirming the intensification of the urban heat island phenomenon and the need for sustainable adaptation measures. The implementation of nature-based solutions—green roofs, rain gardens, green corridors, permeable surfaces can reduce local air temperatures by up to 1.5°C and significantly improve thermal comfort and urban quality of life. The implications of the study are relevant for urban planners, researchers, and decision-makers, providing a replicable framework for climate-smart urban planning. The originality of the paper lies in the integration of smart city technologies and data-driven nature-based solutions into a coherent vision for the climate transformation of Bucharest into a more resilient, sustainable, and future-proof city.

Keywords: climate resilience; smart city; urban heat island; urban sustainability; green infrastructure.

1. Introduction

Climate change is one of humanity's greatest challenges, with a significant impact on the urban environment. Metropolitan areas such as Bucharest are facing phenomena such as heat islands, severe droughts, urban flooding, and air pollution, which, when amplified and combined, lead to a decline in the standard of living in the city [1]. Climate resilience refers to the ability of a system, whether natural, economic, social, or urban, to anticipate, prepare for, respond to, and prevent the effects of climate change, adapting in a way that reduces vulnerability and increases long-term adaptive capacity [2].

In principle, an important aspect of climate resilience is reducing risks and exposure to extreme weather events through responsible land-use planning and, above all, through the implementation of preventive measures. For example: expanding green spaces, increasing permeable surfaces, and protecting vulnerable areas. Infrastructure adaptability is also vital: it must be designed to cope with heat waves, torrential rains, or floods without causing major damage [3].

At the same time, a resilient city is characterised by its ability to recover quickly after an extreme weather event, through adapted policies and the creation of an effective response system, enabling it to recover more quickly than a locality where the grey and unadapted infrastructure encounters difficulties [4].

In this study, we want to raise awareness of the effectiveness of nature-based solutions in urban planning and their benefits. Nature-based solutions (NBS) are actions inspired and supported by nature that simultaneously provide ecological, social, and economic benefits, while contributing to solving major challenges such as climate change, disaster risks, human health, and sustainable development.

Unlike gray infrastructure based solely on rigid technologies such as concrete or asphalt, nature-based solutions are designed to improve urban resilience by reintegrating ecosystem processes into the city structure [5]. These can include, for example, the creation or expansion of urban green spaces such as parks, urban gardens, or urban forests, which contribute to carbon sequestration, temperature reduction, and improved air quality. Another quality would be the reduction of impervious surfaces, such as replacing concrete or asphalt parking lots with permeable paving surfaces where vegetation can penetrate, which can contribute to stormwater management and reduce urban flooding [6].

2. Materials and methods

Because I wanted to implement cartographic material to better observe the temperature differences in Bucharest and the study area, I made a forecast for the hot and cold seasons in Ilfov County and Bucharest [7]. We have an impressive network of nearly 50 amateur weather stations, with free access to this data, throughout the county and municipality (Fig 1).

Fig. 1. Example for Weather Station 5-in-1
Source: www.bresser.com

The data we used are the monthly averages for the months that fall within the warm season, the cold season, and precipitation data. To validate the data obtained from private weather stations, we compared it with that provided by the state data network, from the National Meteorological Administration. To make a forecast, we first need to create the model that we will train and generate the predicted data [8]. This method is based on Machine Learning.

Machine learning is a bunch of math algorithms, also called models, that are trained to try to figure out and find patterns in a set of input data. This mathematical approach has various applications in scientific fields as well as in everyday life. One of the fields that is increasingly using machine learning is medicine, with a variety of applications ranging from detecting diseases to predicting the behavior of molecules [9].

The methodology used has the advantage of simplicity and reproducibility, as the training and inference processes are automated and integrated into the GIS environment, eliminating the need for external scripting. At the same time, this type of approach allows for the spatial assessment of temperature distribution in urban and suburban environments, contributing to the identification of areas at risk of heat islands and urban flooding in support of climate resilience decisions [10].

To create a climate prediction model applicable at the local level, we used point vector data from both ANM weather stations and amateur stations across the study area. The goal was to estimate the average temperature for both seasons based on a set of meteorological data for each month of 2024 [11]. The data was collected and integrated into a single vector layer, which was then grouped into the two seasons. Each point had an associated air temperature value, and the spatial coordinates (latitude and longitude) were kept as implicit explanatory variables in the training process. The model was built using ArcGis Pro cartographic software [12].

To create a spatialized climate prediction model for the Bucharest–Ilfov area, we used the AutoML tools available in ArcGIS Pro, namely "Train Using AutoML" for training the model and "Predict Using AutoML" for applying it to the study area. During the training stage, the Train Using AutoML function was used to automatically generate an optimal regression model, internally testing several algorithms such as support vector machines, decision trees, linear regression, and neural networks. The training used the point locations available in the training dataset, and air temperature was set as the target (dependent) variable. After identifying the optimal model, based on Random Forest, it was applied for prediction. The prediction layer was generated by the Predict Using AutoML function, which estimated the average air temperature values on the generated grid points.

3. Results

The set of maps presented compares the spatial distributions of average maximum temperatures in the warm season for the years 2024 and 2025, as well as the prediction generated by the AutoML model. All three representations highlight the persistence of a strong thermal core in the central area of Bucharest, characterized by particularly high temperature values, which confirms the presence of a pronounced heat island phenomenon (Fig 2 and 3).

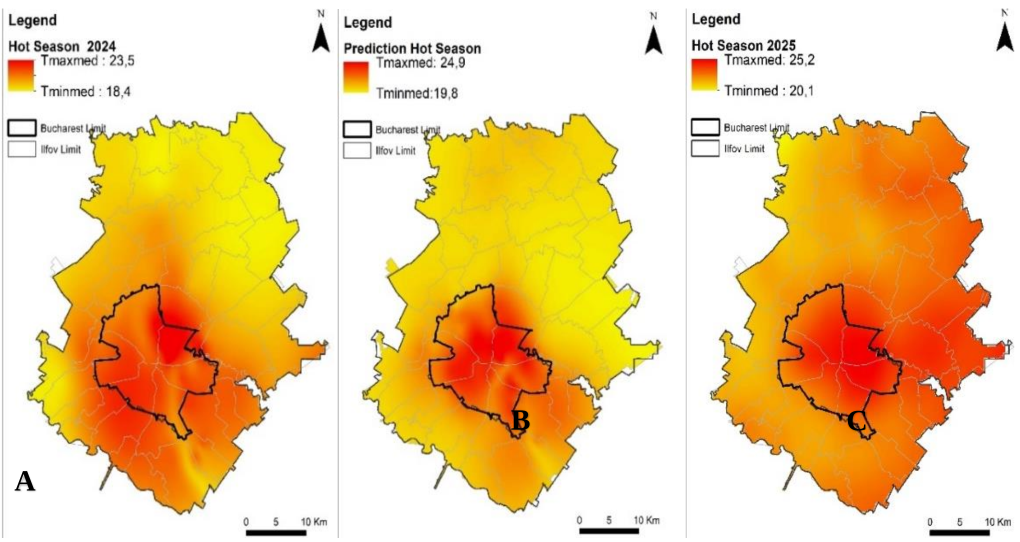

Fig. 2. Spatial distribution of air temperature in the warm season based on observations in 2024(A), AutoML model predictions(B) and air temperature in the warm season based on observations in 2025 (C) for the Bucharest–Ilfov area

Source: Administration National of Meteorology, https://www.wunderground.com/

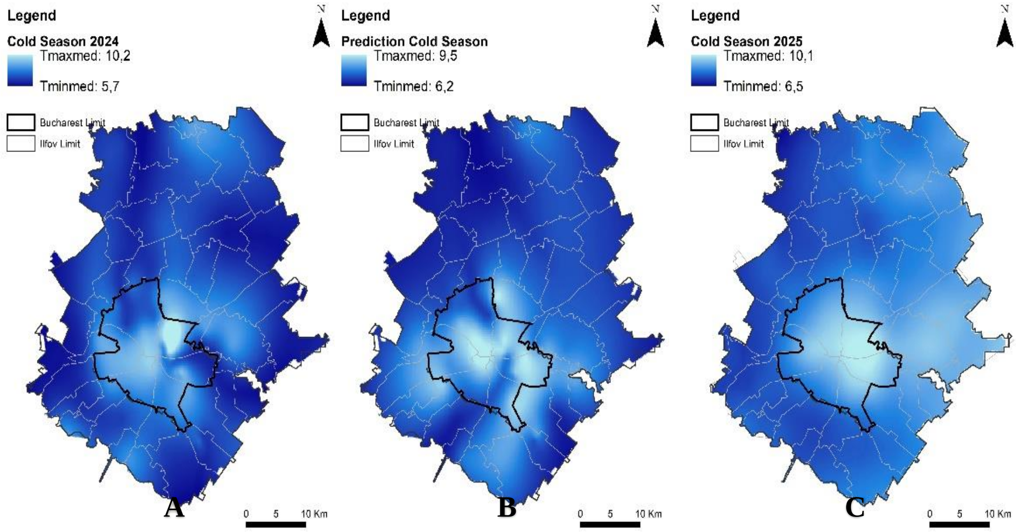

Fig. 3. Spatial distribution of air temperature in the cold season based on observations in 2024 (A), AutoML model predictions(B) and air temperature in the cold season based on observations in 2025 (C) for the Bucharest–Ilfov area

Source: Administration National of Meteorology, https://www.wunderground.com/

From an urban planning perspective, these results highlight the urgent need to implement Nature-Based Solutions to reduce heat island effects. Reducing impervious surfaces, increasing green spaces, ecological corridors, and blue-green infrastructure can significantly contribute to moderating local temperatures. In the absence of coherent interventions, future scenarios indicate an accentuation of thermal contrasts and a decrease in urban resilience.

In the context of Bucharest, SSP scenarios allow local predictions to be placed within a global framework and medium-term climate risks to be estimated [13].

The SSP1-2.6 scenario describes a sustainability-oriented evolution with moderate temperature increase. For Bucharest, this indicates a difference of approximately 0.8°C in the warm season between global and local predictions, respectively a relatively stable precipitation regime, with slight intensifications of summer convective rains [14].

The SSP3-7.0 scenario, characterized by high emissions, signals more pronounced temperature increases of up to 1.2°C in the warm season, as well as a decrease in total precipitation amounts, but with an increase in the frequency of torrential episodes [14].

The most pessimistic scenario, SSP5-8.5, projects the largest temperature differences (over +1°C) and a sharp increase in rainfall extremes: less frequent but much more intense rains, with a high potential for urban flooding,which is relevant for Bucharest [14].

Overall, the use of climate scenarios in local risk assessment highlights the need for accelerated implementation of nature-based solutions, expansion of green-blue infrastructure, and reduction of impervious surfaces to increase Bucharest's climate resilience by 2040 (Fig 4).

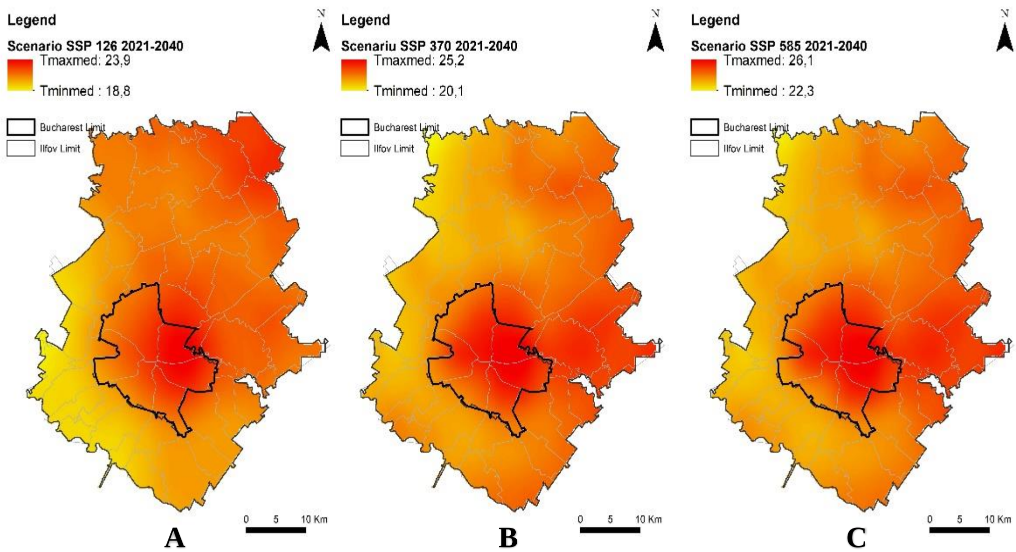

Fig. 4: Spatial distribution of air temperature in the warm season under SSP Scenario 126(A), 370(B) and 585(C) 2021-2040, for the Bucharest - Ilfov area.
Source: IPCC, 2021

To analyze the amount of precipitation, we must consider the average annual values because, the problem in cities is that in a very short time, that is, under 24 hours, amounts of precipitation can fall that reach a monthly value. Their distribution is uneven, due to the size of the city, the influence of the heat island and the number of condensation nuclei, which have a greater influence in the city center and decrease towards the periphery.

After the cartographic determination Fig 5, it can be observed at the level of Bucharest and Ilfov County, the distribution of the amount of precipitation, having a high concentration on the territory of the capital, on the other hand, for the surrounding localities, the distribution of precipitation is more uneven and diminished (Fig 6).

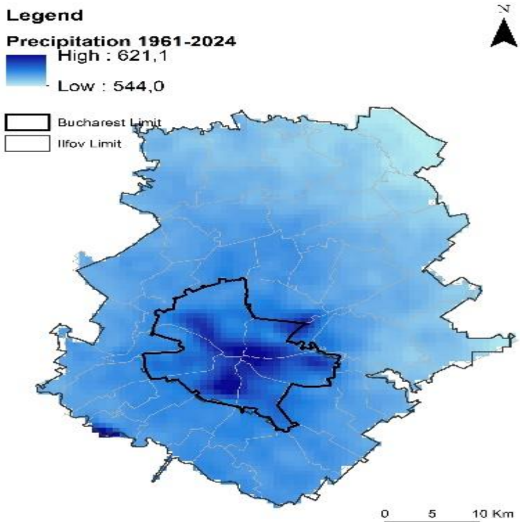

Fig. 5. Precipitation Map of Bucharest
Source: http://www.ecad.eu

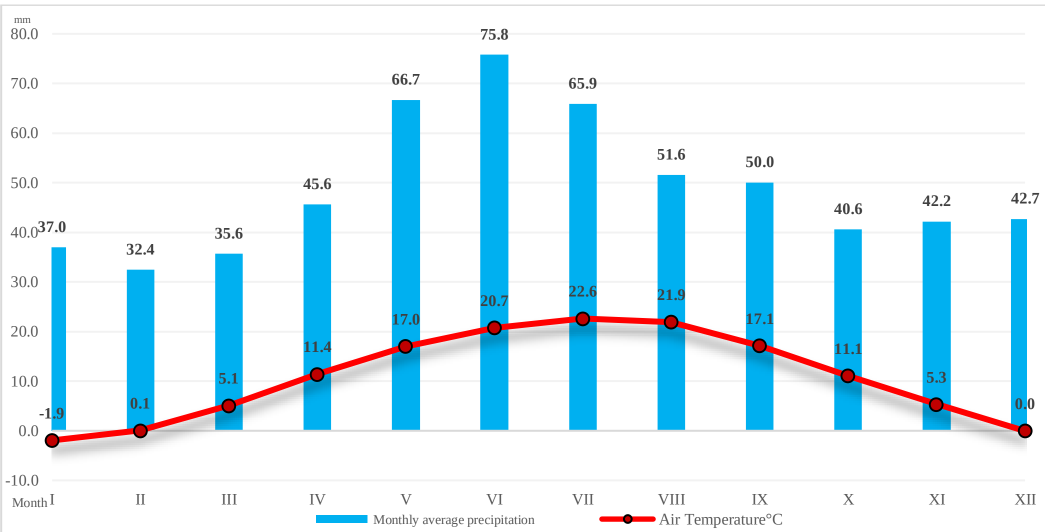

Fig. 6. Average monthly and annual precipitation amounts in Bucharest for the period 1961-2024
Source: http://www.ecad.eu

3.1 Case study - amount of precipitation in 24 hours in Bucharest

During this period at the end of May and beginning of June, the amount of precipitation recorded in less than 24 hours was equivalent to at least one month's worth. The data was collected from several private weather stations in Bucharest, located throughout the urban area, for better coverage. It was also compared with data from the National Meteorological Administration (ANM) for validation, but also for the need for an alternative to redesign the urban landscape (Fig 7 and 8).

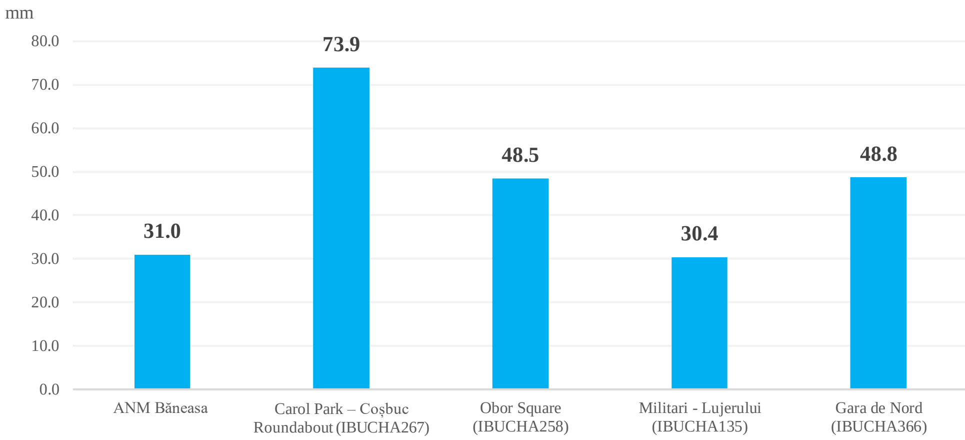

Fig 7: Amount of precipitation in 24 hours in Bucharest - 9.06.2025
Source: Administration National of Meteorology, https://www.wunderground.com/

Fig. 8. Carol Park – Coșbuc Roundabout 9.06.2025
Source: personal archive

4. Discussions

Nature-based solutions can be strategically implemented to combat heat islands, pollution, and urban flooding. In the context of rapid urbanization and the intensification of climate change effects, implementing nature-based solutions is an innovative and sustainable approach to combating the urban heat island effect, reducing the risk of flooding, and improving the quality of the urban environment [15]. One nature-based solution would be green roofs and green facades, which can be implemented on new buildings or shopping centers in the neighborhood. However, as many buildings in the neighborhood are quite old, few buildings can support this kind of weight [16].

However, such solutions are recognized for their ability to reduce local ambient temperatures by up to 1-3 °C, decrease heat transfer inside buildings, and reduce energy consumption for air conditioning [17]. In addition, they contribute to rainwater retention, preventing excessive water accumulation on roofs and relieving the sewer system. [18]. Another solution would be permeable pavements, which are an effective way of increasing water infiltration into the soil, reducing the risk of urban flooding [19]. These could be installed in neighborhood parking areas, both public and private, allowing water to accumulate and filter naturally into the soil [20].

To assess the potential of these solutions, a matrix was developed (Table 1), which correlates the main urban problems (urban heat islands, flooding, air quality, lack of green spaces, and social cohesion) with the estimated effectiveness of each proposed NBS intervention. The color scale was chosen for the following values: red for 0–15%, orange for 15–30%, yellow for 30–45%, and green for over 45%, because here we have much more effective results.

The percentages included in this analysis are not assigned randomly but are based on an analysis of the specialist literature. For example, green roofs have demonstrated up to 35% efficiency in reducing the heat island effect and between 20–30% in stormwater management by lowering local temperatures by up to 3°C and retaining a significant portion of precipitation water [18].

Permeable pavements, suitable for public and private parking lots, can help reduce surface water runoff by up to 80%, but for Bucharest, an efficiency of 35% has been estimated [20].

The trees planted along major boulevards can lower the ambient temperature by 1–4°C and improve air quality by capturing polluting particles, with an estimated efficiency of 45% for cooling and 40% for urban cooling [21].

Community gardens and new urban parks, such as the recently opened Liniei Park, can support ecological and social regeneration, with estimated efficiencies of 25–30% in combating urban heat islands and up to 50% in promoting social cohesion [22].

Tabel 1. Implementation of nature-based solutions in Bucharest

Nature-Based Solution	Urban Heat Island	Air Quality	Urban Flooding	Lack of Green Spaces	Land Use	Observations
Green roofs	35%	20%	25%	25%	10%	Requires buildings suitable for installation; high local cooling impact; moderate stormwater retention
Permeable pavements	10%	5%	35%	20%	5%	Highly effective for flood mitigation; indirectly contributes to urban comfort
Street trees	45%	40%	25%	35%	10%	Provide shading, evapotranspiration, and air filtration; require adequate boulevard space
Community gardens / Parks	30%	25%	20%	50%	50%	Multiple benefits: cooling, social interaction, educational activities
Liniei Park (local example)	30%	25%	20%	50%	50%	Post-implementation studies may reveal real medium-term effects

Source: Tzoulas et al., 2007

4.1 Applicability and case study

Based on field observations, satellite images, and GIS analyses, several types of interventions can be identified. Areas with a high density of impermeable surfaces, such as Lujerului, Păcii, or Gorjului, as well as parking lots in shopping centers, are priorities for the introduction of permeable pavements and linear green infrastructure, such as vegetated swales, hedges, etc. Unused spaces between blocks of flats can be small green squares and offer opportunities for socialising and increasing shaded areas. We have identified potential areas and a specific type of nature-based solution aimed at reducing the urban heat island effect and improving the quality of urban life [17]. These solutions include planting rows of trees along the main boulevards: Preciziei, Timișoara, Valea Cascadelor, and Sos-Virtuții. These interventions are intended to provide shade, filter the air, and reduce temperatures at pedestrian level.

It is also proposed to extend Liniei Park westward, on Liniei Street, in the new phase of the neighborhood, with the aim of creating a functional green corridor that will enhance social and ecological connectivity (Fig 9).The rehabilitation of Grozăvești Park, located near the eastern edge of the neighborhood, would contribute to the revitalization of an existing green space through modern ecological improvements and increased rainwater storage capacity. At the same time, I would propose the installation of green roofs on new buildings and shopping centers, such as Plaza România, Afi Cotroceni, or Auchan Militari, with the aim of reducing heat accumulation and increasing water retention. These interventions, proposed based on the urban specifics of the neighborhood, such as high density, heavy traffic, and lack of vegetation, contribute to the formation of a concrete green infrastructure network, essential for increasing the climate resilience of the Militari neighborhood and improving the urban microclimate.

Fig. 9. Localization of nature-based solution proposals.
Source: Personal archive

4.2. Limitations of case study

One of the main problems with implementing nature-based solutions is the old buildings in the neighborhood, where implementing the concept of green roofs would add extra weight to their structural integrity. Another problem identified is the excessive urbanization of the area, where it is difficult to implement a system of solutions distributed evenly throughout the Militari neighborhood.

5. Conclusion

Bucharest faces an uneven and deficient distribution of green spaces, which amplifies the negative effects of climate change, such as urban heat islands, decreased air quality, and increased risk of flooding. This study highlights the importance and urgency of implementing nature-based solutions that are tailored to the real needs of the area's residents. The analysis and consultation of documentation and examples of good practice highlight the fact that the residents of the neighborhood want, as a priority, the creation of new spaces that will improve both the urban microclimate and the quality of life.

Green spaces help reduce local temperatures through plant transpiration, regulate rainfall, and reduce surface runoff, while also providing essential social and environmental benefits. They support the physical and mental health of the population, reduce stress, and create opportunities for relaxation, social interaction, and recreational activities. In addition, green solutions such as parks can transform unused or degraded spaces into areas with a major positive impact on the community.

In conclusion, implementing these solutions in Bucharest is not only a sustainable choice, but a vital necessity for increasing climate resilience, adapting to heat waves, and continuously improving the quality of urban life. Green spaces must become a priority in the neighborhood's urban development strategy, responding both to current climate challenges and to residents' aspirations for a healthy, sustainable, more aesthetic, and climate-resilient urban environment.

References

[1] European Environment Agency, „The European environment: state and outlook 2020 : executive summary," Publications Office, Luxemburg, 2019.

[2] A. Lucie, „Building systemic climate resilience in cities," 2023.

[3] E. Andersson, „Urban climate resilience through hybrid infrastructure," *Curr. Opin. Environ. Sustain,* vol. 55, p. 101158, apr 2022.

[4] G. N. De Lima, M. A. Fonseca-Salazar și J. Campo, „Urban growth and loss of green spaces in the metropolitan areas of São Paulo and Mexico City: effects of land-cover changes on climate and water flow regulation," *Urban Ecosyst,* vol. 26, nr. 6, pp. 1739-1752, dec 2023.

[5] C. Stefano, „The new advanced Cities From the Green and Digital to the Smart Cities," 2022.

[6] M. R. Christopher, „A framework for assessing and implementing the co-benefits of nature-based solutions in urban areas," 2023.

[7] M. C. Suciu și D. F. Năsulea, „Smart cities & crowdsourcing. A bottom-up approach," 2018.

[8] C. Săvulescu, „Fostering the digital change in a smart city," 2017.

[9] A. Jovic, K. Brkic și N. Bogunovic, „A review of feature selection methods with applications," în *2015 38th International Convention on Information and Communication Technology, Electronics and Microelectronics (MIPRO),* Opatija, Croatia, 2015.

[10] ESRI, „Introduction to deep learning," 2023. [Interactiv].

[11] I. F. Voicu, D. C. Diaconu și D. C. Diaconu, „Precision long-term monitoring of local weather at household level," 2024.

[12] C. Vrabie, „E-Government 3.0: An AI Model to Use for Enhanced Local Democracies," *Sustainability,* vol. 15, nr. 12, p. 9572, iun 2023.

[13] K. Riahi, „The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview," *Glob. Environ. Change,* vol. 42, pp. 153-168, ian 2017.

[14] IPCC , „Climate Change 2021: The Physical Science Basis," Cambridge University Press, Cambridge, 2021.

[15] I. A. Dogeanu, „Designing with purpose: The advocacy for sustainable and resilient architecture," 2024.

[16] M. R. Niţă, C. Ioja și A. M. Popa, „Searching for the Perfect Balance in the Multifunctionality of Urban Green Parks," în *Making Green Cities*, M. A. C. I. ș. S. Q. J. Breuste, Ed., Cham, Springer International Publishing, 2023.

[17] F. Nemèșanu și F. Pînzaru, „Smart City Management based on IoT," *Smart Cities and Regional Development (SCRD) Journal,* vol. 1, nr. 1, p. 91–97, Oct 2017.

[18] M. Köhler, „Green facades—a view back and some visions," *Urban Ecosyst,* vol. 11, nr. 4, pp. 423-436, dec 2008.

[19] V. Baltac, „Smart Cities—A View of Societal Aspects," *Smart Cities,* vol. 2, nr. 4, pp. 538-548, dec 2019.

[20] S. E. Gill, J. F. Handley, A. R. Ennos și S. Pauleit, „Adapting Cities for Climate Change: The Role of the Green Infrastructure," *Built Environ,* vol. 33, nr. 1, pp. 115-133, mar 2007.

[21] D. E. Bowler, L. Buyung-Ali, T. M. Knight și A. S. Pullin, „Urban greening to cool towns and cities: A systematic review of the empirical evidence," *Landsc. Urban Plan,* vol. 97, nr. 3, pp. 147-155, sep 2010.

[22] K. Tzoulas , „Promoting ecosystem and human health in urban areas using Green Infrastructure: A literature review," *Landsc. Urban Plan,* vol. 81, nr. 3, pp. 167-178, iun 2007.