

EVOLUTION OF CITIES UNDER CLIMATE CHANGE: GREENING AND BLUE-GREEN INFRASTRUCTURE



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Abstract: Every year the world's population moves more and more to cities. Today 56% of all people live in cities, the forecast for 2050 suggests an increase in this figure to 60%. Sustainability for urban development is critical, as it addresses such issues as water and air pollution, waste management and resource consumption. Green cities use environmentally friendly practices to promote the health of the urban environment and, as a result, improve the quality of life. Nature-based solutions represent an interdisciplinary issue, including the competencies of urban planners, landscape designers, engineers, hydrologists, ecologists, economists, etc. and are critically needed for climate change adaptation.

The paper is focused on the role of blue-green infrastructure as key adaptation strategy for climate change. Innovative approaches and technologies as examples of the best urban management strategies promoting a more sustainable urban environment resistant to climate change will be presented and discussed.

Keywords: urban development, climate change, mitigation and adaptation, blue-green infrastructure, ecosystem services.

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Introduction

Cities have always attracted people, becoming economic engines, centers of trade, culture, and innovation. The benefits are also related to utilizing human capital, shared infrastructure, and division of labour [1]. Some 56% of the global population (4.4 billion inhabitants) already lives in cities, and by 2050, two-thirds of the world's population are expected to live in urban areas, which is projected to increase to around 9.8 billion¹ [2]. There is a strong relationship between urbanization and income: as countries get richer, they tend to become more urbanized. Therefore, urban populations tend to have higher living standards [3–6]. Today, megacities occupy about 3% of the earth's surface but at the same time consume two-thirds of the world's energy and other resources. The consumption of materials by the planet's cities (all raw materials mined in the territory per year plus imports minus exports) will increase from 41.1 billion tons in 2010 to 88.8 billion tons by 2030. The cities are the largest contributors to climate change, creating about 70–75% of anthropogenic carbon dioxide emissions. Despite all their power and wealth, cities are extremely vulnerable to climate disasters [7]. The modern process of urbanization is characterized, first of all, by a deterioration of the urban environment. The purpose of this paper was to analyse the development of blue-green infrastructure in the city of Krakow and its role in shaping the urban environment in terms of improving the quality of life of city residents and adaptation to climate change. The aim was achieved based on the case studies of the development and transformation of urban areas in Krakow, Poland.

Urban areas as techno-ecosystems

Urban population growth, especially in recent decades, turned out to be so rapid that the environment of many cities in the world is no longer able to satisfy many biological and social needs of the people. The big

¹ United Nations, Department of Economic and Social Affairs, Population Division, 2018.

cities change almost all components of the natural environment – topography, water resources, atmosphere, soils, and even climate. Cities concentrate people, infrastructure, and many other resources in a limited space – this makes them more vulnerable to natural phenomena. In addition, there are typical urban problems: air and water pollution and the generation of various types of waste. Dense urban development, urban transport, and a lack of green spaces contribute to the emergence of heat islands. This phenomenon is caused by sealed surfaces (asphalt, concrete) "absorbing" heat and not allowing surface runoff to pass through. This process is intensified by climate change: the average annual temperature is rising, and abnormal heat waves are occurring more frequently. At the same time, the demand for air conditioning increases, which means greater energy production, respectively. More hydrocarbons must be processed to meet demand, resulting in higher emissions of air pollutants and greenhouse gases (Fig.1).

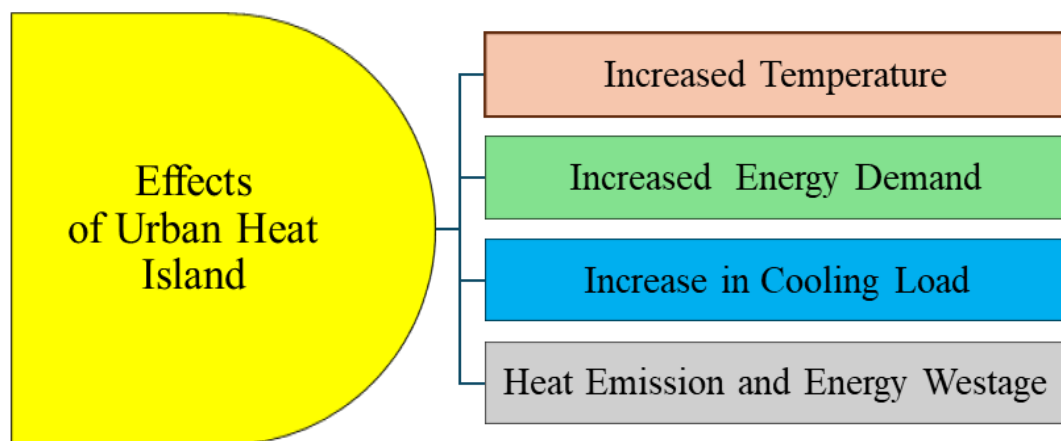


Fig. 1. *Negative effects of urban heat islands [8]*

Many cities also suffer from a shortage of fresh water. According to the World Resources Institute, 17 countries, home to a quarter of the world's population, have extremely high levels of water stress. The demand for energy and water is increasing due to population growth, socio-economic development, and urbanization, while climate change makes this problem even more critical. All this harms the comfort of life and health of the population. From an environmental point of view, a modern city is a tangle of acute contradictions with the need to seek difficult compromises. First of all, the process of urbanization deals a severe blow to the fragile ecological balance. The main problems in urban areas are presented in Figure 2 [9].

The urban environment becomes the basic condition for human life. A healthy urban environment favourable for people and nature ensures the physical, psychological, and social comfort of residents, harmonious and sustainable social and economic development of the city.

The urban ecosystem is an unstable natural-anthropogenic system, consisting of architectural and construction sites and severely disturbing natural ecosystems. If the first ones provide comfort of life for a modern city dweller, the latter, on the contrary, reduce its quality [10]. The city develops special microclimatic conditions inherent in individual areas of the urban area. The formation of the city's microclimate is also influenced by the conditions created by urban development, as well as city transport, thermal power plants, industrial and other enterprises. The major factors of city microclimate formation are the following: (1) topography changes; (2) difference in thermophysical properties of the surfaces of urban elements and natural environment; (3) difference in albedo of underlying surfaces of the city territory and surroundings; (4) artificial heat flows; (5) air pollution; (6) reduced evaporation due to sealed surfaces; (7) sharp decrease of surface area with vegetation and natural soil [11].

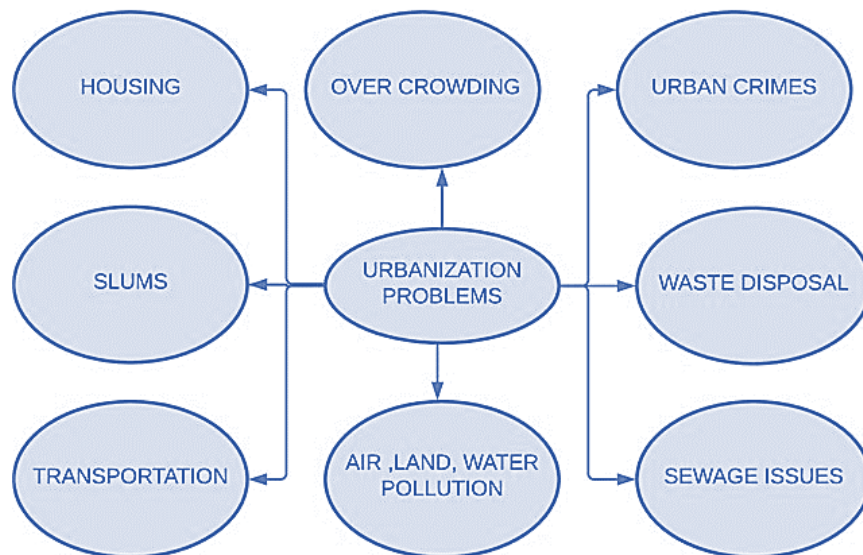


Fig. 2. The main social and environmental problems in urban areas [9]

Urban development vs climate change

Cities influence climate both at local and global levels and, in turn, are themselves subjected to the consequences of climate change. Cities contribute to global climate change by releasing greenhouse gases through heating, cooling, transport, and industry. As cities grow, they are increasingly exposed to the risks of climate change, especially in the absence of rational development planning. The new urban development program adopted at the third UN conference on housing and sustainable development defines sustainable cities as "providing protection, preserving, restoring, and shaping ecosystems, water resources, natural habitat, and biological diversity, minimizing environmental impact, and providing the transition towards sustainable consumption and production patterns"². The number of activities required to achieve the goal of sustainable urban development is presented in Figure 3 [12].



Fig. 3. The basic activities towards transformation to sustainable urban development (on the base of [12])

Blue-green infrastructure

One of the tools for urban areas adaptation to climate change is creating blue-green structures. Urban green infrastructure planning (UGI) is a strategic approach to develop interconnected and multifunctional networks of blue and green spaces that potentially provide a wide range of environmental, social and economic benefits and simultaneously enhance the climate resilience of cities³. Already now, "blue-green infrastructure" can act as a systemic approach to address the problems of pollution, habitat, recreation, and urban development. Integrating the green (soft areas, plants, and trees) with the blue (watercourses, ponds, lakes, and storm drainage) elements makes the urban spaces more resilient, pleasant, and healthy places to live, work, and

² Habitat III: New Urban Agenda. Quito, Ecuador, October 2016.

³ Urban green infrastructure planning and nature-based solutions. DG CLIMA Project Adaptation Strategies of European Cities (EU Cities Adapt), Climate-ADAPT, 2024.

leisure. The development of such infrastructure in cities helps to increase the flow of benefits from ecosystem services and is an important trend in the formation of a "green" economy (Fig.4) [13].

Trees, parks, and gardens are not only compatible with cities but undoubtedly must be an integral part of densely populated urban areas. Trees and other plant species create many benefits, such as restoration of the water cycle, reduction of CO₂ emissions, and air purification, all of which have aesthetic value and improve the quality of life⁴.

The conservation and restoration of natural ecosystems has a long history but is not always perceived as a tool for climate change mitigation. One way to

adapt to climate change is to use the stabilizing role of natural ecosystems. Modern large cities are practically devoid of natural ecosystems. They are trying to adapt to new conditions primarily through "grey" infrastructure (i.e., engineering structures and technologies) that require significant resources and are often mono-functional. It is cheaper, more efficient, and more durable for cities to turn to solutions created by nature itself. Such solutions can be implemented by replacing "grey" infrastructure with "green" and "blue" ones, that is, creating, preserving, and properly using green areas and water bodies.

However, in order to achieve the effect of "green" infrastructure, strategic planning is necessary taking into account local specifics, ensuring the creation and maintenance of a continuous water-green framework of the city as a single system. Spatial planning has a key role in addressing the causes of climate change.

Materials and Methods

To achieve the intended goal, the following research methods were used: the monographic method, document examination method, diagnostic survey method, and case-by-case method. The analysis was carried out based on data obtained from the Municipal Green Area Management Board in Krakow for the period 2018-2024 (statistical data on the number, types, and surface of urban green areas, urban greenery maps, and others).

Results and Discussion

Case Study: Approach to Urban Greening and Blue-Green Infrastructure in Krakow

Examples of urban greening, implementation of blue-green infrastructure, and Nature-Based Solutions (NBS) can be found in cities around the world that are actively pursuing sustainable development and adaptation to climate change. Krakow, a historic city in southern Poland with a population of approximately one million, is one of them. The actions taken in Krakow towards achieving climate neutrality and enhancing the city's resilience to the impacts of climate change can serve as a model to follow.

In recent years, the Municipality of Krakow (GMK) has implemented a series of policies, strategies, and plans aimed at creating an environmentally friendly and sustainable urban space in the city. These documents have redefined the goals to be achieved and the priorities for actions through 2050, with a particular emphasis on achieving climate neutrality. For this purpose, Krakow has decided to join the "Mission 100 Climate-Neutral and Smart Cities" by 2030. To reach this goal, the city has developed a "Climate Contract," which serves as an action plan for achieving climate neutrality by 2030. The target is to reduce CO₂ emissions by

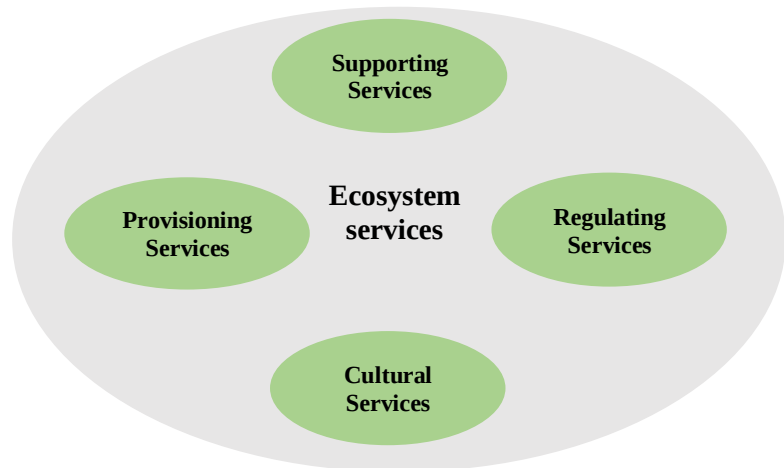


Fig. 4. Ecosystem services in urban areas [13]

⁴ Summary of the 21st Session of the Committee for the Review of the Implementation of the Convention of the UN Convention to Combat Desertification. Earth Negotiations Bulletin, 4 (303), 2023

80% by 2030 compared to the base year of 2018. The city's efforts are currently progressing according to plan, making the achievement of this target seem realistic.

One of the city's main strategic objectives is to increase the proportion of green areas within developed spaces, enhance forest cover, and improve residents' access to these areas. To accelerate the achievement of environmental and climate goals, GMK established two specialized organizational units: the Municipal Greenery Authority (2015), focused on the development and management of green spaces in Krakow, and the municipal unit Climate-Energy-Water Management (2020), dedicated to reducing greenhouse gas emissions and adapting Krakow to climate change. As a result of the efforts of these two municipal units, supported by other municipal organizations, over 376,500 trees and more than 818,000 shrubs and climbers have been planted in Krakow since 2015. Since 2018, 28 new city parks have been opened to the public, and 24 existing parks have been modernized. Additionally, 27 new pocket parks, 18 new community gardens, and 6 "Krakowian Parks" have been established.

As part of the city's afforestation plan for 2018-2024, the forested area within the city's boundaries has increased from 4% to nearly 5%, with a target of achieving a forest cover rate of at least 8% by 2040. All investment activities undertaken to green the city simultaneously improve residents' access to recreational public green spaces, which now total 2,526,000 m². Currently, 85% of Krakow residents have access to public green areas larger than 0.5 hectares within a straight-line distance of no more than 300 meters. A summary of current data on parks and gardens located in Krakow is presented in Table 1^{5,6,7,8,9,10,11}.

Table 1. Summary of Basic Information on Urban Parks and Gardens in Krakow for the Years 2018 and June 2024

Type of Green Space	Number		Area
	2018	June 2024	[ha]
Parks	43	75	835,19
Pocket Parks (Krakowian Gardens)	16	43	11,65
Forests	-	-	1590,39
Community Gardens	3	21	-
Krakowian Parks	0	6	-

An essential parameter indicating a city's resilience to climate change is the biologically active surface area ratio. In Krakow, this indicator currently stands at 72% of the city's total area, which is 327 km².

Equally important as urban greening for building climate resilience is a city's ability to manage and absorb rainfall effectively to prevent localized flooding and manage drought conditions during dry periods. To achieve this, the city of Krakow continuously implements measures to restore natural retention systems in highly urbanized areas. The primary objective is to manage stormwater so that it is retained as much as possible at

⁵ Zarząd Zieleni Miejskiej w Krakowie: Krakowska zieleń w liczbach.
<https://zsm.krakow.pl/?view=article&id=1606&catid=111>

⁶ Zarząd Zieleni Miejskiej w Krakowie: Lista parków miejskich.
<https://zsm.krakow.pl/images/pliki/PLIKI%20PDF/Parki.pdf>

⁷ Zarząd Zieleni Miejskiej w Krakowie: Lista parków kieszonkowych.
<https://zsm.krakow.pl/images/pliki/PLIKI%20PDF/parki%20kieszonkowe%206.24.pdf>

⁸ Zarząd Zieleni Miejskiej w Krakowie: Powierzchnia lasów miejskich.
<https://zsm.krakow.pl/nowe-lasy/1524-informacja-o-powierzchni-lasow-w-krakowie.html>

⁹ Zarząd Zieleni Miejskiej w Krakowie: Mapa krakowskich ogrodów społecznych.
<https://zsm.krakow.pl/dla-krakowian/ogrody/krakowskie-ogrody-spoeczne/1090-mapa-krakowskich-ogrodow-spoecznych.html>

¹⁰ Zarząd Zieleni Miejskiej w Krakowie: Lokalizacje parków krakowian.
<https://zsm.krakow.pl/wspoldzialanie/parki-krakowian.html>

¹¹ Zarząd Zieleni Miejskiej w Krakowie: Mapy lasów zlokalizowanych na terenie Gminy Miejskiej Kraków.
<https://zsm.krakow.pl/lasy-w-krakowie-na-mapach.html>

the point of precipitation (within the local catchment area), and where this is not feasible, to delay the outflow of stormwater from the local catchment area to the greatest possible extent.

To this end, Krakow is undertaking a range of investment activities focused on developing a comprehensive blue-green infrastructure. This includes the construction of retention basins, depressions, ponds, bioretention ditches, infiltration ditches, rain gardens, green roofs, facades, walls, permeable pavements, and structural soils. Where necessary, impermeable surfaces are being replaced with permeable ones. All these actions are preceded by thorough analyses of water flow in local catchments using advanced numerical hydrodynamic models. These models not only help to identify potential flood-prone areas but also optimize the placement of technical solutions to enhance the retention capacity of each catchment.

Examples of Developing and Transforming Urban Green Spaces

Railway Park in the City Center

In 2017, a railway link was introduced in downtown Krakow, connecting two separate railway lines into a unified system to serve regional and agglomeration rail services. The railway link comprises three viaducts with a total length of over one kilometer and two bridges with a length of 155 meters. The link is supported by 30 pillars up to 15 meters high and uses 28 steel spans with a maximum span of 81 meters (Fig 5). Beneath the viaduct, between the pillars, a new open space with an area of 20,000 m² was created. Following public consultations, this space has been designated as Railway Park, which will also serve as a pedestrian and bicycle route connecting two adjacent city districts (Fig.6).



Fig. 5. Aerial view of the railway link, beneath which Railway Park is planned to be developed ¹²



Fig. 6. Visualization of a section of the Railway Park beneath one of the viaducts ¹³

In accordance with the residents' wishes, the park has been divided into functional zones, determined by various spatial and architectural factors such as the height of the pillars, the width of the viaduct, and the surrounding environment. The design includes the creation of an educational trail focusing on the history of railway transport development in Poland, complemented by graphic elements that also serve to enhance the monochromatic pavement and concrete elements of the viaduct. Along the entire length of the railway link, a series of green zones with different functionalities will be developed beneath the viaducts. These will include, among other things: a playground in the form of a railway town, a sensory garden, a dog park, a recreational area, bicycle parking facilities, a meeting area, a multifunctional zone (including services, retail, and cultural spaces), a sports zone (featuring basketball, soccer, fitness areas, and a skatepark), and a community garden¹⁴. All these zones will be surrounded by tall and low greenery, as well as flowering meadows. The park is currently under development.

¹² Ministerstwo Infrastruktury: https://www.gov.pl/static/mi_arch/2-514324a4ec938-1798072-p_32.html

¹³ Zarząd Zieleni Miejskiej w Krakowie: <https://zzm.krakow.pl/>

¹⁴ Ministerstwo Infrastruktury: https://www.gov.pl/static/mi_arch/2-514324a4ec938-1798072-p_32.html

Zakrzówek Park – Urban Swimming Area

The park was established around a former quarry, now filled with crystal-clear water (Fig.7). It has become one of the city's favorite recreational spots. Zakrzówek Park covers an area of 50 hectares, and together with adjacent areas, the blue-green space spans approximately 100 hectares¹⁵. The park features charming walking trails, viewpoints, and running paths equipped with water fountains. It also offers extensive opportunities for cyclists and rock climbers. In recent years, the park has introduced Krakow's first public swimming area of this kind. The swimming facility consists of openwork pools on the surface of the reservoir, with varying depths, allowing for swimming both for proficient swimmers and those who are not, as well as a 40-cm-deep pool designed for children¹⁶.

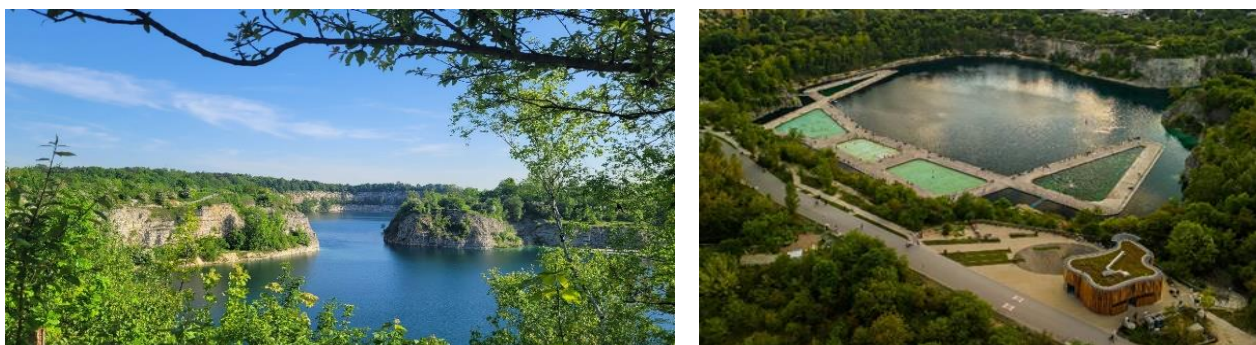


Fig. 7. Zakrzówek Park ^{17,18}

Pocket Gardens

Pocket gardens in Krakow are small green spaces developed in various parts of the city, primarily on previously unused or underutilized plots. This initiative aims to increase greenery in densely built urban areas, improve air quality, and create recreational spaces for residents. These gardens are often designed with environmental sustainability in mind, incorporating native plant species and sometimes including educational elements, such as informational boards about local fauna and flora.

Krakow features several unique pocket gardens, each with its own theme. The Fairy Tale Garden (Fig.8) draws inspiration from fairy tales, incorporating elements that evoke children's literature and create a magical atmosphere.



Fig. 8. The Fairy Tale Garden ¹⁹



Fig. 9. The Chess Garden²⁰

The Chess Garden (Fig.9) includes chess tables amid greenery, encouraging residents to engage in intellectual outdoor activities. The Weed Garden (Fig.10) showcases the beauty of wild plants and weeds, often undervalued, highlighting their role in the urban ecosystem. The Chestnut Garden (Fig.11) centers around

¹⁵ Zarząd Zieleni Miejskiej w Krakowie: <https://zsm.krakow.pl/>

¹⁶ Ibid.

¹⁷ Zarząd Zieleni Miejskiej w Krakowie: <https://zsm.krakow.pl/>

¹⁸ Zalew Zakrzówek i Uroczysko Skałki Twardowskiego.
<https://cudnapolska.pl/zalew-zakrzowek-i-uroczysko-skalki-twardowskiego/>

¹⁹ Zarząd Zieleni Miejskiej w Krakowie: <https://zsm.krakow.pl/>

²⁰ Zarząd Zieleni Miejskiej w Krakowie: <https://zsm.krakow.pl/>

chestnut trees, with their leaves and fruits forming a distinctive element, providing a tranquil space for relaxation under the tree canopies. These gardens enrich the urban landscape, offering diverse aesthetic and educational experiences^{21,22}.



Fig. 10. The Weeds Garden ²³



Fig. 11. The Chestnut Garden ²⁴

Community Gardens

Community gardens are shared green spaces created and maintained by residents. Their primary roles are to foster social integration, provide ecological education, and promote sustainable living. These gardens offer opportunities for growing vegetables, herbs, and flowers and serve as venues for meetings, workshops, and cultural events, thus strengthening community bonds.

One example is the Wild Explorers Space (Fig.12). This garden combines recreational and educational functions, particularly aimed at children. It features a variety of installations and natural elements designed to encourage young visitors to explore nature and learn through play. The space is designed to stimulate creativity and curiosity about the world while fostering ecological awareness from an early age.

Another community garden, located in Kurdwanow, is dedicated to the collective cultivation of plants by residents. This garden serves as a place that fosters integration and the exchange of experiences among its users (Fig.13).

The garden at the Kraków City Hall, on the other hand, offers a more tranquil setting where residents and municipal employees can relax amidst greenery and participate in various ecological initiatives (Fig.13).



Fig. 12. Community Garden - Wild Explorers Space ²⁵

²¹ Zarząd Zieleni Miejskiej w Krakowie: Lista parków kieszonkowych.
<https://zzm.krakow.pl/images/pliki/PLIKI%20PDF/parki%20kieszonkowe%206.24.pdf>

²² Zarząd Zieleni Miejskiej w Krakowie: <https://zzm.krakow.pl/>

²³ Ibid.

²⁴ Ibid.

²⁵ Zarząd Zieleni Miejskiej w Krakowie: <https://zzm.krakow.pl/>



Fig. 13. Community Garden – Kurdwanow (left) and Community Garden – at the Krakow City Hall (right) ²⁶

Revitalization of Streets and Squares

One of the more notable projects undertaken by the city was the revitalization of Krupnicza Street, located in the heart of Krakow. The goal of these revitalization efforts was to create a space that is welcoming to all residents – pedestrians, cyclists, and businesses operating on the ground floors along the street. The guiding principle behind the changes was based on the concept of a woonerf – a street with traffic-calming measures where pedestrian safety is prioritized while still accommodating vehicular traffic. This goal was achieved by creating a shared space for all users through the elimination of curbs and the traditional separation of roadway and sidewalk. Traffic calming was further supported by the integration of street furniture and green spaces.

Rainwater harvesting systems were installed along the street, with collected water used to irrigate new plantings during dry periods. Additionally, rain gardens were established along the entire length of the street. The street surface is constructed from granite paving stones, occasionally supplemented by historical basalt cobblestones recovered during demolition work. Embedded within the paving are copper plates providing information on significant historical and cultural facts related to Krupnicza Street (Fig.14).



Fig. 14. Krupnicza Street before (left) and after (right) revitalization ²⁷

Another example of urban greening is the revitalization of the area around the Market Hall in Grzegorzki, Krakow. This project aims to transform the area into a modern and functional urban space. It involves updating infrastructure, enhancing the aesthetics of public spaces, and introducing new elements of street furniture. However, the most crucial aspect is increasing the amount of green space through tree planting, creating small parks and gardens, and constructing green roofs on tram stops. These measures are intended to modify the local microclimate and reduce the urban heat island effect (Fig.15).

²⁶ Zarząd Zieleni Miejskiej w Krakowie: <https://zzm.krakow.pl/>

²⁷ Whitemad. Available at: <https://www.whitemad.pl/zniknely-auta-powstal-deptak-ulica-krupnicza-w-krakowie-po-metamorfozie/>



Fig. 15. The area around Market Hall in Grzegorzki before (left) and after (right) revitalization ²⁸

Blue-Green Infrastructure

In Krakow, a variety of blue-green infrastructure solutions are being implemented to integrate vegetation with stormwater management systems. Examples of such solutions include urban parks and green spaces, such as the Park of Polish Aviators (Fig.16), which serve both retention purposes by storing stormwater and recreational functions, enhancing air quality. Other examples include green roofs on public buildings, residential blocks, office buildings, and public transport stops, as well as green walls. For many years, Krakow has been constructing retention tanks and rain gardens aimed at capturing stormwater and reducing runoff into sewage systems. These solutions support local biodiversity and contribute to cooling urban areas on hot days.



Fig. 16. Park of Polish Aviators – an example of a pond as a component of blue-green infrastructure ²⁹

Conclusion

Climate change necessitates innovative approaches to urban planning and development. Urban greening and the implementation of nature-based solutions (NBS) are becoming crucial components of adaptation strategies aimed at enhancing the resilience of urban environments to these changes. Effective adaptation requires an interdisciplinary approach, integrating knowledge from urban planning, hydrology, ecology, and engineering. An example of a city that has long pursued an ambitious pro-climate policy is Krakow. Through numerous initiatives related to greening and managing storm water, the city aims not only to improve the quality of life for its residents but also to enhance its resilience to climate change. The priority is retention, green and blue infrastructure, maintenance and revitalization of parks, afforestation, etc. The analysis of the presented examples of investments implementation in the field of blue-green infrastructure in Krakow clearly shows the city's commitment to the application of the "sponge city" strategy. Increasing biologically active

²⁸ Lovekrakow. Available at: <https://lovekrakow.pl/aktualnosci/zdjecie/51359>

²⁹ Zarząd Zieleni Miejskiej w Krakowie: <https://zsm.krakow.pl/>

areas plays an extremely important role in the functioning of urban ecosystems. Greening cities allows for the achievement of the following strategic ecological, economic, and social goals:

- 1) restoring the natural water cycle and water balance in the city,
- 2) mitigation of the urban heat island phenomenon,
- 3) shaping a comfortable microclimate of the city,
- 4) improving of the general ecological situation,
- 5) adaptation to the adverse effects of climate change,
- 6) improvement of the urban technical infrastructure functioning (e.g., wastewater networks, highways),
- 7) rational management of rainwater and its use for different municipal needs,
- 8) increasing the safety and life quality of residents,
- 9) social integration of residents,
- 10) creation of additional employment places.

Lack of funding is consistently cited as a barrier to green infrastructure implementation. However, one of the advantages that green infrastructure projects offer is that they bring so many benefits that they can compete for a variety of different funding sources. Some tax incentive programs administered by federal agencies can be used to attract funding for green infrastructure projects. The city of Krakow's long-standing commitment to the development of blue-green infrastructure was honoured in 2022 with an award in the Eco-City competition organised by the French Embassy in Poland and the UNEP/GRID-Warsaw Centre.

Conflict of Interest

The authors declare no conflicts of interest

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