

Urbanization in Beijing: Challenges and Sustainable Solutions for Water Scarcity and Urban Heat Islands

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Abstract. As globalization and economic development accelerate, urbanization has become an inevitable trend, radically transforming global societal structures and economic models while profoundly impacting the environment and human lifestyles. This study delves into the rapid urbanization of Beijing, China, highlighting its significant effects on environmental and ecological aspects. Employing an analytical approach, this paper examines the process of urbanization in Beijing, focusing on changes in the urban environment, water resource challenges, and the urban heat island (UHI) effect. Key findings reveal that Beijing's urban expansion has led to critical issues such as severe water scarcity and intensified UHI effect, with significant implications for ecological well-being and sustainable urban development. This research underlines the importance of balanced urban growth and environmental sustainability, advocating for integrated strategies including enhanced flood monitoring systems, accelerated development of water recycling facilities, and the adoption of the sponge city concept. These measures not only aim to improve water resource efficiency and urban flood resilience but also mitigate the UHI effect through increased urban green spaces and high-albedo building materials. The study offers valuable insights and lessons for global cities facing similar challenges. The study emphasizes the need for comprehensive, systemic approaches to urbanization that harmonize economic, social, and environmental aspects. This paper contributes to the broader discourse on sustainable urban development, offering a framework for future urban planning and policy-making that prioritizes ecological safety and improves the quality of life for urban residents.

Keywords: Urbanization Impact, Urban Heat Island Effect, Water Resource, Sustainable Urban Development.

1. Introduction

As globalization and economic development progress, urbanization has become an inevitable trend. Currently, the pace and scale of urbanization worldwide have reached unprecedented levels. As of 2018, over half of the global population resides in urban areas, according to the United Nations. This trend is expected to continue, with the proportion of the global urban population increasing to 68% by 2050[1]. This migration fundamentally alters social structures and economic development models, profoundly impacting the environment and human lifestyles. While urbanization offers more job opportunities, educational resources, medical services, and cultural activities to residents, its often uncontrolled growth brings severe environmental consequences. Research shows that the impact of urbanization on the environment is complex and multidimensional, often exceeding the scale of urban population growth itself. These impacts include changes in land use, increased waste, and pollution of air and water [2].

China, the nation with the greatest population in the world, has significantly influenced the global level of urbanization with its urbanization process. Based on a report published by the Chinese Bureau of Statistics, China's rate of urbanisation stood at 60.6% at the end of 2019. The rapid advancement of urbanization in China, especially in its Special Economic Zones and coastal cities, has set new benchmarks in global urbanization trends. However, the rapid urbanization of major cities in China, particularly Beijing, has also brought a series of challenges. As one of the fastest urbanizing metropolises in China, Beijing's urbanization rate increased from 54.93% in 1978 to 87.55% in 2021.

This city expansion has not only harmed ecosystems by providing possible ecological dangers, but it has also hampered sustainable urban development [3]. These challenges include uneven resource

distribution, environmental pollution, traffic congestion, housing issues, and immense pressure on infrastructure. Accompanying the urbanization process are the substantial demands for water resources and changes in urban ecological environments, evident in Beijing as water scarcity, intensified UHI effects, and degradation of the ecological environment.

Therefore, this article aims to delve deeply into how Beijing's urban expansion affects its ecological environment, as well as potential solutions and countermeasures. The article primarily focuses on analyzing Beijing's urbanization process, environmental changes, and ecological impacts. It seeks to offer insights and lessons to other cities around the world, assisting them in better protecting their ecological environments and achieving sustainable development during their urbanization processes.

2. The Urbanization Process of Beijing

With the rise of finance, information technology, and cultural and creative industries, Beijing is transforming from a traditional political and cultural center into an international innovation hub. As one of the largest cities in the world, Beijing has seen rapid urban growth since the 1980s. The permanent population increased from about 9 million in 1980 to 21 million in 2019, while the urban area expanded from roughly 184 km² in 1973 to 3686 km² in 2015[4]. Large areas of green space and water bodies have been replaced by urban infrastructure. Rapid transit systems, wide highways, and towering buildings depict Beijing's modernization. In addition to its expanded geographical space and growing population, Beijing's urbanization is also reflected in profound changes in its economic activities and social structure. The city's modernization has led to a more diversified economic structure, promoting the development of the service and high-tech industries.

However, the rapid development of the economy and society is accompanied by environmental and resource pressures. Beijing faces challenges in water resource management, including river pollution, over-extraction of groundwater, and declining water quality. Recorded observations indicate steadily decreasing precipitation, particularly in the vicinity of Miyun Reservoir, Beijing's main water supply source [4]. The cumulative effect of these problems has led to issues of water supply security, forcing the government and various sectors of society to take measures to ensure the sustainable use of water resources. At the same time, the expansion of urban spaces often leads to the reduction of ecosystem services. For example, natural areas like wetlands and forests, which can regulate climate, and filter air and water, are covered by hard building surfaces. This not only reduces the city's biodiversity but also diminishes its capacity to counteract the UHI effect, which causes the temperature in urban areas to rise above that of adjacent rural areas. The UHI effect not only affects the comfort and health of residents but also impacts urban climate change and sustainable development. Beijing's example highlights the importance of adopting sustainable development measures amidst rapid urbanization to maximize the benefits of urbanization while reducing negative impacts on the environment and society.

3. Impact of Urbanization Expansion

This section focuses on the significant impacts of Beijing's urbanization expansion on water resources and the UHI effect. The urbanization process has not only increased the demand and consumption of water resources but also altered precipitation patterns and water quality, putting pressure on the water supply system. Moreover, urbanization, characterized by increased construction and road surfaces and reduced green spaces, has triggered the UHI effect, which raises urban temperatures and affects residents' lives and the urban climate.

3.1. Water Resources

Beijing faces the majority of the issues that big cities deal with, like extreme river pollution, excessive groundwater extraction, and contaminated water resources [5]. The availability of water

resources per person in Beijing fell from 300 m³ in 2000 to 100 m³ in 2011, resulting in serious problems with the security of the water supply [5].

Beijing has a temperate monsoon climate. Surface water and groundwater replenishment mainly come from surface precipitation, which is seasonal, with hot, rainy summers. Thus, the main causes of Beijing's annual precipitation decrease is the notable decrease in summer precipitation and warm-season rainfall. The urban expansion in Beijing, as mentioned earlier, leads to the UHI effect, increasing surface temperatures, enhancing sensible heat flux, and deepening the boundary layer, thereby reducing evaporation and consequently decreasing summer precipitation in Beijing [4]. Since 2000, with the expansion of Beijing, the annual average precipitation has gradually decreased. Over the 12 years from 1999 to 2011, the annual average precipitation decreased by 17.8% from 481 millimeters, compared to the average of 585 millimeters over the 44 years from 1956 to 2000, resulting in a 44% reduction in available water resources in 2011, down to 2.1 cubic kilometers [5].

Beijing used 3.6 billion m³ of water annually in 2011 compared to 1 billion m³ in 2000, an increase of about 230 million m³ per year due to the city's rapid economic expansion, growing urban population, and rising living standards [5]. The enormous demand and reduced rainfall have led to a water resource shortage, resulting in the over-extraction of a large amount of groundwater. Most urban rivers in Beijing have low water levels for most of the year. Between 1999 and 2012, the groundwater level in the urban plain, which includes the city center, dropped by more than 1 m annually, from 11.7 m below the surface to 24.3 m [5]. This leads to a reduction in the water volume of wetlands and rivers, causing damage to wetland ecosystems and the drying up of rivers.

Additionally, urban expansion leading to changes in land use has negatively impacted water quality. Beijing's construction land grew 2.65 times between 1995 and 2011, from 4158 hectares to 11000 hectares. According to studies by Gao et al., nitrogen discharge in the Guishui River Basin in Beijing increased by 11.6% between 1995 and 2011, going from 117.2 tons to 130.8 tones [6]. This rise which led to the eutrophication of water bodies, and degrading water quality was caused by an increase in built-up area per unit area [6]. The plains region's 3,058 km² of shallow groundwater aquifers were designated as class IV–V water in 2014, which means that these waters are only fit for industrial and agricultural use and should not be drunk. However, only 761 km² of deep groundwater was classified as class IV–V, comprising roughly 22% of the area under observation [7]. The primary causes of non-compliant groundwater are surface pollution sources, geological background, and declining groundwater levels [8]. The expansion of water pollution has led to a reduction in usable water resources, exacerbating the water crisis in the Beijing area.

Notably, urbanization creates large areas of impermeable surfaces, which obstruct the infiltration process of rainfall, increase surface runoff, and accelerate the concentration of water flow. Combined with the UHI effect, this leads to a higher frequency of concentrated heavy rainfall, causing regular flooding incidents in cities [7]. This not only causes significant human casualties but also results in substantial economic losses. Addressing the severe flooding issues caused by such storm events remains a significant challenge.

3.2. UHI Effect

The UHI effect reflects the impact of urban growth on surface temperatures and is one of the major ecological effects associated with urbanization. This phenomenon is especially evident in rapidly urbanizing cities like Beijing and may further affect the health of Beijing's residents and local climate patterns.

As the urban land area increases, the intensity of the UHI typically rises. This is due to larger urbanized areas having more concrete, asphalt, and other impermeable surfaces (ISA) that absorb and retain heat [9]. Research have shown that important variables influencing changes in Land Surface Temperature (LST) are changes in urban land use, including an increase in built-up area, impermeable surfaces like rooftops and marble surfaces, and a decrease in vegetation cover [10]. This is because of the building materials' thermal characteristics that store heat during the day and the removal of vegetation and the 'waterproofing' of surfaces, which leads to reduced evaporation and, consequently,

an increase in sensible heat flux [11]. According to research by Wang et al., the surface albedo in urban areas of Beijing remains almost consistently at 0.12 throughout the year, which is 3% to 8% lower than in rural areas [11]. This implies that urban surfaces absorb more solar radiation and convert it into heat energy, thus increasing the surface temperature.

Wang et al. divided Beijing into four areas: core, expanded, newly developed, and ecological. The first two are urbanized, while the latter two are non-urbanized [12]. From Fig. 1, it is evident that with the continuous urbanization of Beijing, the Impervious Surface Area (ISA) has expanded from 1448 km² in 1980 to 3686 km² in 2015. The increase is concentrated in Beijing's core and extended zones, while the ecological areas have not shown a significant rise.

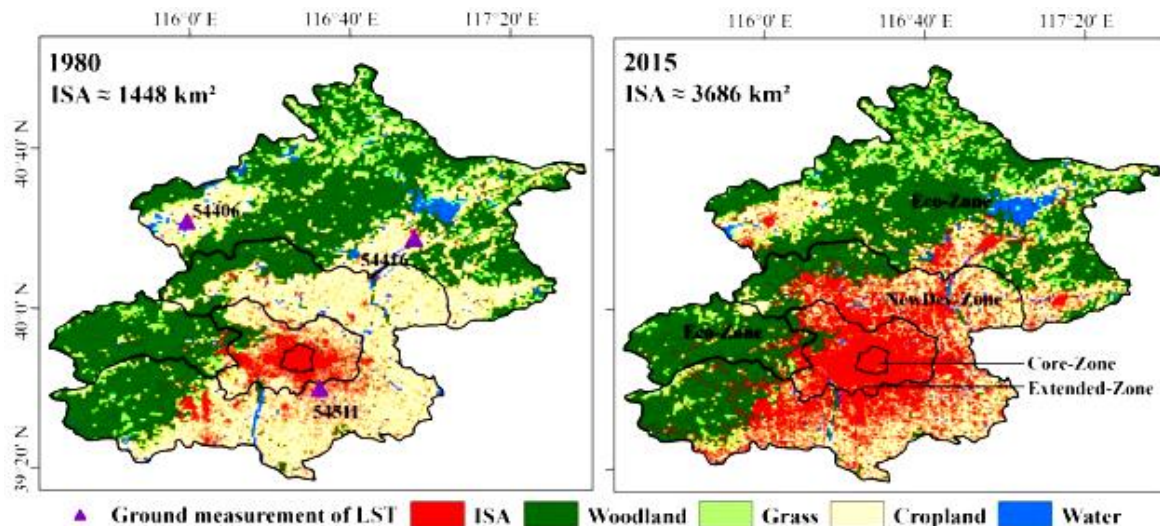


Figure 1. Shows the change in the area of LST measurements and ISA in Beijing from 1980 to 2015 [12].

Further research has found that over the decades from 1980 to 2020, LST has also significantly increased, reaching 11.2°C in 2020 from 10.3°C in 1980. It is important to note that this temperature shows spatial variations across different areas, with the highest average surface temperature in the core areas at about 17.2°C, and the lowest in the ecological areas at 9.4°C. The LST in non-urbanized ecological areas, starting from a baseline of 10.7°C in 1980, has experienced a smaller increase over the years. In particular, the ecological area has only seen an increase of 0.04°C, reflecting the natural temperature variation unaffected by urban development. From 1980 to 2020, the average LST difference (LSTD) between "urbanized" and "non-urbanized" areas in Beijing was about 0.2°C. The most significant difference was in the extended zones (~0.9°C), and the smallest in the ecological zones (~0.04°C). Over time, these differences have shown an increasing trend, especially in the extended zones (0.033°C/year) and newly developed areas (0.016°C/year), where urban expansion has reshaped the thermal phenology of these areas [12]. The core and ecological areas have the smallest increase, less than 0.002°C per year. Wang, et al. also indicate that UHI intensity is highly correlated with the urban land area [10]. However, within a certain city size, the more compact the urban form, the more pronounced UHI effect. The shift of UHI is generally consistent with the shift in the urban land center of gravity. The quick conversion of suburban land into urban land is thought to be the cause of the UHI effect. The expansion of urban land also creates a larger urban heat island area than the city itself. Notably, the core areas of urban land use, although having the highest average surface temperatures, have seen a smaller increase over the years. This is because these areas have essentially completed urbanization, with little change since 1980. In summary, surface temperatures will worsen with the expansion of the city, threatening residents' comfort. Worse still, the change in surface temperatures caused by the city may overlap with global warming, raising the risk of overheating even further.

4. Solution

In response to the UHI effect and water scarcity issues brought about by urbanization in Beijing, this study proposes the following integrated strategies and solutions to address the challenges posed by urban expansion. In terms of water resources, this includes utilizing advanced technology to improve flood monitoring capabilities, accelerating the construction of water recycling plants, and promoting the concept of sponge cities, all aimed at optimizing the water cycle and enhancing the effective use of water resources. To mitigate the UHI effect, this section suggests increasing urban green spaces and using high-albedo building materials to lower surface temperatures, along with sensible urban planning and landscape design to improve the city's temperature regulation capacity. Future urban development needs to continue such diversified strategies to ensure sustainability and the well-being of residents.

4.1. Protection and Rational Use of Water Resources

Firstly, from the perspective of enhancing flood monitoring, modern tools such as radar river gauges and Acoustic Doppler Current Profilers (ADCP) are used to monitor and forecast floods more accurately. These tools support a new mode of unmanned hydrological monitoring and have been validated in multiple standardized water measuring sections [8]. Though the Beijing hydrological automation system was first put into place in 2006, the parameters in the flood monitoring and prediction model should be regularly modified in light of changes brought about by urbanization in terms of soil moisture, groundwater levels, and surface conditions [8]. Its real-time data can be quickly transmitted to the municipal water affairs bureau, providing crucial data support for urban water use and drainage during the flood season.

Secondly, the construction of water recycling plants is accelerated. In addition to developing new wells and diverting water from the Yangtze River Basin to alleviate Beijing's water shortage, recycled water has recently become Beijing's second-largest water source [8]. By the end of 2015, recycled water was gradually considered an important supplementary water source for Beijing. By that time, 47 new water recycling plants were built in urban and suburban centers and some large cities, with a total new sewage treatment capacity reaching 832 million cubic meters. All newly built water recycling plants must ensure that the treated recycled water reaches Grade IV quality standards, which means it can be purified to meet usage standards through appropriate treatment processes, ensuring the safe use of recycled water [8].

Lastly, there is support for the development of sponge cities. The government of China proposed in 2014 that water should be absorbed, stored, permeated, and purified by urban surfaces, and then released for usage as needed [13]. Sponge city construction uses materials with high permeability, which can compensate the shortcomings of traditional drainage networks and widely used concrete surfaces, such as pervious concrete and asphalt for roads, squares, and parking lots, allowing rainwater to infiltrate directly into the ground to replenish groundwater. In addition, the construction of green roofs, rain gardens, and wetlands is a key part of building sponge cities; they can absorb and store rainwater, reducing the risk of urban waterlogging, while also providing recreational and relaxation spaces for urban residents.

4.2. Mitigation of the UHI Effect

Urban Flood Management (UFM) techniques, according to certain studies, have significant synergistic advantages, such as reducing the UHI effect [7]. For instance, in the process of constructing sponge cities to solve the water crisis and flooding, reducing the area of impermeable surfaces and increasing urban green spaces not only enhances the infiltration in the water cycle but can also raise the city's surface albedo to lower urban surface temperatures. Additionally, planners can choose roads and building surface materials with high reflectivity, such as white or light-colored asphalt, which effectively reduces the absorption of sunlight and lowers urban temperatures. The USA and The viability of enhancing albedo with light-colored roofs and pavements has been

thoroughly studied commercially in Europe, and since 2000, there have been established industry standards for these kinds of products [14]. Urban green spaces and green roofs can also reduce temperatures through evaporation and transpiration, providing a comfortable microclimate for residents. According to research by Tian et al., efficient landscape design may create urban cool islands out of urban green spaces, which helps to reduce the impact of the UHI effect [15]. Additionally, they discovered that wetlands effectively regulate temperature, with the degree of temperature regulation increasing with proximity to an urban wetland [15]. Thus, in order to direct changes in land use in urban areas and modify the urban thermal environment, policymakers should also set reasonable landscape configurations when developing new urban areas, such as being near water sources, integrating with urban forestry, and limiting local urban density.

5. Conclusion

This study thoroughly analyzes the environmental changes in Beijing's urbanization process, particularly the issues of water scarcity and the UHI effect, and discusses multidimensional solutions. In the wave of urbanization, Beijing's development has not only led to population growth and urban spatial expansion but also triggered profound challenges for the environment and resources. The analysis and recommendations of this aim to provide references for Beijing and other cities around the world when facing similar challenges.

The current practices in Beijing concerning water resource management and alleviating the UHI effect reveal a critical reality: a balance must be struck between the continuity of urban development and environmental sustainability. The surge in urban population and industrial activities has led to a shortage and decline in water quality, while the increasing impermeable surfaces and high-density buildings in the urbanization process have intensified the UHI effect. To address this, the proposes measures in water resource management, such as enhancing flood monitoring and early warning systems, accelerating the construction of water recycling facilities, and promoting the concept of sponge cities, with Beijing striving to improve water resource efficiency and urban flood resilience. In mitigating the UHI effect, strategies such as increasing urban green spaces, selecting high-albedo building materials, and sensible urban planning not only enhance urban ecological safety but also optimize the living environment for residents.

Looking ahead, the ongoing advancement of urbanization must adopt a more comprehensive and systematic approach to meet its challenges. This includes but is not limited to, optimizing urban planning, strengthening the enforcement of environmental protection regulations, promoting technological innovation and application, implementing cross-sector collaboration, fostering public participation and environmental education, and establishing long-term monitoring and assessment systems. Through these measures, it is possible to achieve a coordinated development of the economic, social, and environmental aspects of urbanization. Beijing's practices and experiences provide valuable insights into environmental management in the global urbanization process. Only through comprehensive governance involving policy, technology, planning, and societal participation can the path of urbanization be sustainable, thus benefiting both current and future residents. Ultimately, as global urbanization deepens, these experiences will promote a more livable, healthy, and green urban future.

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