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RESEARCH ARTICLE

THE CONCEPT OF THE SPONGE CITY AS AN ELEMENT OF ECOLOGICALLY SUSTAINABLE URBANISM

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Abstract. *In the context of accelerating climate change, rapid urbanisation, and the increasing frequency of hydrometeorological hazards, the Sponge City concept has emerged as a promising framework for sustainable and nature-based urban development. The present study seeks to reconsider conventional technocratic approaches to stormwater management through the integration of natural hydrological processes into the structure of urban infrastructure. The methodological framework combines comparative and systems-based analysis of international practices with the examination of the principles of Low Impact Development (LID) and Water Sensitive Urban Design (WSUD). The research employs Sentinel-2 satellite imagery, ArcGIS Pro spatial analysis tools, and quantitative runoff assessment methods based on land-use structure and hydrological coefficients. The projects Harbin Qunli Stormwater Park, Yanweizhou Park, and Bishan–Ang Mo Kio Park was selected as representative case studies. The findings demonstrate that the integration of permeable surfaces, bioretention systems, water-retention landscapes, and green infrastructure contribute to runoff reduction, microclimatic improvement, and enhanced ecological performance of the urban environment. The study confirms that the Sponge City concept establishes a new paradigm of sustainable urbanism in which water is interpreted as a strategic resource for spatial development. Nature-based solutions increase urban resilience to climatic and infrastructural risks and may be effectively applied within environmentally and seismically vulnerable territories.*

Keywords: *Sponge City, blue-green infrastructure, Low Impact Development (LID), Water Sensitive Urban Design (WSUD), stormwater management, bioretention, climate resilience, sustainable urbanism.*

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ҒЫЛЫМИ МАҚАЛА

ГУБКА-ҚАЛА ТҰЖЫРЫМДАМАСЫ ЭКОЛОГИЯЛЫҚ ТҰРАҚТЫ УРБАНИЗМНІҢ ЭЛЕМЕНТІ РЕТІНДЕ

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Аңдатпа. *Климаттық өзгерістердің күшеюі, урбандалу үдерістерінің қарқындауы және гидрометеорологиялық қауіптердің артуы жағдайында Sponge City тұжырымдамасы тұрақты әрі табиғатқа негізделген қалалық дамудың перспективалы моделі ретінде қарастырылады. Зерттеу дәстүрлі технократиялық жаңбыр сулары менеджменті тәсілдерін қайта пайымдауға және табиғи механизмдерді қалалық инфрақұрылым құрылымына интеграциялауға бағытталған. Әдіснамалық негізін халықаралық тәжірибені салыстырмалы және жүйелік талдау, сондай-ақ Low Impact Development (LID) және Water Sensitive Urban Design (WSUD) қағидаларын зерттеу құрайды. Зерттеу барысында Sentinel-2 спутниктік деректері, ArcGIS Pro кеңістіктік талдау құралдары және жер пайдалану құрылымы мен гидрологиялық коэффициенттер негізінде беткі ағынды сандық бағалау әдістері қолданылды. Harbin Qunli Stormwater Park, Yanweizhou Park және Bishan–Ang Mo Kio Park жобалары талданды. Зерттеу нәтижелері су өткізгіш жабындарды, биоретенциялық аймақтарды, су ұстап тұратын ландшафтарды және жасыл инфрақұрылымды енгізу беткі ағынды азайтуға, микроклиматты жақсартуға және қалалық ортаның экологиялық тұрақтылығын арттыруға ықпал ететінін көрсетті. Sponge City тұжырымдамасы суды кеңістіктік дамудың стратегиялық ресурсы ретінде қарастыратын тұрақты урбанизмнің жаңа парадигмасын қалыптастыратыны анықталды. Табиғатқа негізделген шешімдер қалалардың климаттық және инфрақұрылымдық қауіптерге төзімділігін арттырып, экологиялық және сейсмикалық тұрғыдан осал аумақтарда қолданылуы мүмкін.*

Түйін сөздер: *Sponge City, көк-жасыл инфрақұрылым, Low Impact Development (LID), Water Sensitive Urban Design (WSUD), нөсерлік ағын суларды басқару, биоретенциялық жүйелер, климаттық орнықтылық, тұрақты урбанизм.*

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НАУЧНАЯ СТАТЬЯ

КОНЦЕПЦИЯ ГОРОДА-ГУБКИ КАК ЭЛЕМЕНТ ЭКОЛОГИЧЕСКИ УСТОЙЧИВОГО УРБАНИЗМА

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Аннотация. *В условиях усиливающихся климатических изменений, урбанизации и увеличения гидрометеорологических рисков концепция Sponge City рассматривается как перспективная модель устойчивого и природоориентированного городского развития. Исследование направлено на переосмысление традиционных технократических подходов к управлению ливневыми водами и интеграцию природных механизмов в структуру городской инфраструктуры. Методологическую основу составляют сравнительный и системный анализ международного опыта, а также исследование принципов Low Impact Development (LID) и Water Sensitive Urban Design (WSUD). В работе использованы спутниковые данные Sentinel-2, инструменты ArcGIS Pro и методы количественной оценки поверхностного стока на основе структуры землепользования и гидрологических коэффициентов. Проанализированы проекты Harbin Qunli Stormwater Park, Yanweizhou Park и Bishan–Ang Mo Kio Park. Результаты показали, что интеграция проницаемых покрытий, биоретенционных зон, водоудерживающих ландшафтов и зелёной инфраструктуры способствует снижению поверхностного стока, улучшению микроклимата и повышению экологической устойчивости городской среды. Установлено, что концепция Sponge City формирует новую парадигму устойчивого урбанизма, в которой вода рассматривается как стратегический ресурс пространственного развития. Природоориентированные решения повышают резильентность городов к климатическим и инфраструктурным рискам и могут быть применены в экологически и сейсмически уязвимых территориях.*

Ключевые слова: *город-губка, сине-зелёная инфраструктура, развитие с низким воздействием на окружающую среду (LID), водочувствительное городское проектирование (WSUD), управление ливневыми стоками, биоретенция, климатическая резильентность, устойчивый урбанизм.*

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1 INTRODUCTION

In the early twenty-first century, cities found themselves at the epicentre of global climatic transformations. Modern urban environments are increasingly confronted with the consequences of technogenic development, including flooding, overheating of artificial surfaces, and the gradual disappearance of natural ecosystems. The city, once perceived as a symbol of humanity's triumph over nature, is now revealing its vulnerability to climate and water. The traditional model of urban planning, formed during the era of industrial modernisation, was based on the principle of total engineering control over the natural environment. Within this paradigm, water was regarded primarily as a threat that had to be rapidly diverted beyond urban territory. Concrete collectors, rigid drainage systems, and the sealing of soil surfaces progressively displaced natural mechanisms of infiltration, retention, and self-purification. As a result, urban landscapes gradually lost their ecological resilience, while the relationship between infrastructure and nature became increasingly fragmented.

The growing vulnerability of cities demonstrates the necessity of rethinking the relationship between architecture, infrastructure, landscape, and water. Within this context, the Sponge City concept acquires particular relevance, interpreting the urban landscape not as an inert artificial shell but as a living hydro-ecological system capable of accumulating, purifying, and redistributing water within the urban fabric. Similar to the way ecological parks and landscape systems in China transform the destructive force of water into an instrument of urban resilience and environmental regeneration, this paradigm seeks to restore the city's lost capacity for interaction with nature. Water, therefore, ceases to be viewed solely as an engineering problem and becomes an integral component of the ecological and spatial structure of the city, shaping a new philosophy of sustainable urban development [1].

Contemporary research in Kazakhstan likewise emphasises environmentally oriented and climate-resilient urban development [2]. The scientific problem of this research lies in the contradiction between traditional technocratic approaches to stormwater management and the contemporary requirements of environmentally sustainable urban development. For decades, drainage infrastructure was designed primarily for the rapid removal of stormwater from urban territories. However, this approach has resulted in overloaded drainage networks, soil erosion, deterioration of water quality, disruption of the natural hydrological cycle, and the destruction of ecological connections within the urban environment.

Under conditions of increasing climate instability, there is a pressing need to transition towards integrated water-management models in which natural elements become full-fledged components of urban infrastructure. The Sponge City concept proposes a fundamentally different approach to urban organisation, where rain gardens, wetlands, permeable surfaces, and green corridors function as a unified ecological water-management system capable not only of accumulating and purifying water, but also of shaping a new spatial identity of the city. Nature-based systems, therefore, seek not to suppress natural processes through engineering means, but rather to establish a harmonious interaction between the urban fabric and the environment. At the same time, contemporary urban resilience increasingly requires integrated approaches capable of addressing interconnected environmental and infrastructural risks. In this context, the principles of nature-based urbanism may also be considered applicable to broader resilience strategies within environmentally vulnerable urban territories. This issue is particularly significant for Almaty, where increasing environmental and infrastructural risks require the development of resilient approaches to urban planning. The integration of ecological infrastructure into the urban fabric may contribute to improving the adaptability and sustainability of densely built urban territories.

Within this framework, adaptive public spaces may be interpreted as elements of a broader urban resilience system. Linear public parks may be interpreted as multifunctional infrastructure combining ecological, recreational, and adaptive urban functions within resilient city planning. Under normal conditions, such spaces operate as green public corridors, while during emergencies, they may transform into autonomous coordination centres equipped with water reserves, emergency energy

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systems, medical assistance zones, and temporary rescue infrastructure. Thus, the Sponge City paradigm may be interpreted more broadly, not only as a hydrological model of water-sensitive urbanism, but also as part of a wider philosophy of adaptive and resilient city planning in the face of the environmental and technological challenges of the twenty-first century.

The aim of this research is the theoretical interpretation and systematisation of contemporary approaches to the implementation of the Sponge City concept and the identification of its potential for the formation of sustainable and environmentally adaptive urban landscapes. Particular attention is devoted to the relationship between engineering, ecological, and architectural-spatial solutions capable of ensuring urban resilience under conditions of climate change and increasing environmental risks.

To achieve this aim, the following research objectives have been identified:

- to analyse the theoretical foundations of nature-based water management, including the principles of Low Impact Development (LID) and Water Sensitive Urban Design (WSUD);
- to examine international experience in implementing the Sponge City concept through realised projects in China and Singapore;
- to evaluate the effectiveness of integrating natural and engineering solutions in reducing hydrological risks and forming sustainable urban ecosystems;
- to determine the applicability of Sponge City principles within environmentally and seismically vulnerable urban territories.

2 MATERIALS AND METHODS

Recent reports confirm that the application of Low Impact Development and green infrastructure strategies can significantly reduce stormwater runoff volumes and restore natural infiltration capacity within urbanised environments [3]. However, the principal conclusion of these studies lies not merely in the engineering efficiency of such solutions, but in recognising the need to reintegrate ecological mechanisms into the structure of the contemporary city. Within this concept, water is no longer perceived as a threat requiring immediate removal beyond urban territory, but rather as a fundamental component of ecological balance and sustainable spatial development.

Studies devoted to the implementation of Sponge City projects in Chinese megacities emphasise that modern cities are gradually transforming into increasingly self-regulating hydro-ecological systems in which green infrastructure, bioretention zones, rain gardens, wetlands, and permeable surfaces function as interconnected elements regulating microclimate and water balance [4-5]. Recent ecological studies additionally demonstrate that hydrological evolution significantly influences the structure, stability, and ecological dynamics of microbial ecosystems, confirming the importance of long-term ecological processes within water-sensitive environments [6].

Research highlights that the integration of green corridors, water spaces, and biological ecosystems forms a model of blue-green infrastructure in which architecture, landscape, and hydrology function as a unified ecological system [7]. Similarly, nature-based urban water systems, including Sponge Cities and blue-green infrastructures, significantly improve stormwater regulation, ecological performance, and urban resilience while simultaneously enhancing the environmental quality of public spaces [8]. Contemporary urban resilience is increasingly understood not merely as infrastructural stability, but also as the adaptive capacity of cities to respond to environmental, social, and spatial challenges [9]. Recent studies additionally emphasise the social dimension of blue infrastructure within sustainable urban development. Nature-based blue infrastructure contributes not only to flood mitigation and climate resilience but also to improving environmental awareness and the quality of public space in large metropolitan areas [10]. Similar tendencies may also be observed in the urban environment of Almaty, where the spatial organisation and planning structure of public open spaces significantly influence pedestrian connectivity, recreational activity, and the formation of the city's ecological framework [11].

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Of particular interest are realised projects of nature-based urbanism that have become symbolic representations of the ecological paradigm of the twenty-first century. Harbin Qunli Stormwater Park and Yanweizhou Park, designed by Turenscape under the direction of Yu Kongjian, demonstrate a fundamentally different approach to the interaction between nature and the city. Degraded and flood-prone territories were transformed into ecological systems in which the landscape simultaneously performs engineering, environmental, and social functions. Water is no longer isolated through concrete channels, but becomes part of the living structure of public space.

A similar idea is demonstrated by Bishan–Ang Mo Kio Park, implemented within the framework of the ABC Waters Programme. A traditional concrete drainage canal was transformed into a natural river landscape incorporating biofiltration, ecological drainage, and recreational spaces. Much like regional architecture once sought harmony between climate, nature, and humanity, contemporary nature-based projects restore the city's interaction with the natural environment through integration rather than suppression. Within the present research, the Sponge City concept is examined not merely as an engineering strategy for regulating surface runoff but as a new philosophy of urban development based upon adaptability, ecological sustainability, and the restoration of environmental balance.

Research devoted to the role of nature-based solutions under conditions of climatic extremes raises the question of transitioning from isolated engineering systems towards integrated socio-ecological models of urban development [12]. In this context, the limitations of technocratic infrastructure detached from environmental processes are becoming increasingly evident. Particular attention is devoted to nature-based solutions as instruments of climate adaptation, environmental justice, and urban resilience. In this context, the Sponge City concept may be regarded as a contemporary model of environmentally adaptive urbanism in which ecological processes become an integral component of spatial organisation and contribute to the formation of resilient urban environments. Recent studies additionally demonstrate that Sponge City policies contribute not only to flood mitigation, but also to improving ecological welfare through the development of climate-resilient urban water systems [13].

The present study examines three of the most representative examples of nature-based solutions implemented within the framework of the Sponge City concept: Harbin Qunli Stormwater Park, Yanweizhou Park, and Bishan–Ang Mo Kio Park. In contemporary scientific literature, these projects are regarded not merely as urban parks or landscaped public spaces, but as significant examples of the transformation of the urban environment into self-regulating ecological systems in which water becomes an integral component of spatial organisation rather than an engineering threat [14–17]. Furthermore, they reflect broader contemporary trends in sustainable and smart urban development, where environmental resilience, technological innovation, and improvements in quality of life are increasingly recognised as interconnected outcomes of urban transformation [18].

The selection of the case-study objects is determined not only by their international recognition within the field of sustainable urbanism, but also by their typological comparability. All three projects represent urban parks simultaneously performing the functions of ecological infrastructure, water retention, biofiltration, and stormwater regulation. However, of principal importance is the difference in climatic conditions and urban contexts within which these projects were implemented. Much like the traditional architecture of arid regions emerged as a response to extreme climatic conditions, Sponge City projects represent a contemporary form of adaptation of the urban environment to increasing climatic risks associated with urbanisation, stormwater overloads, and the disruption of natural water balance.

Research emphasises the necessity of comparing nature-based engineering solutions across different climatic zones, since the effectiveness of blue-green infrastructure elements directly depends upon precipitation patterns, temperature regimes, seasonal dynamics, and the structure of the urban fabric. For this reason, the selected projects make it possible to trace how a unified concept of nature-based urbanism adapts to different environmental and spatial conditions [1; 4; 18]. The empirical basis of the research was formed using Earth remote-sensing data and open-access project documentation data. Spatial analysis was conducted using Sentinel-2 satellite imagery with a spatial resolution

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of 10 m covering the period from 2018 to 2024, ensuring data comparability and enabling the identification of structural features of land-cover patterns within the investigated territories. In this context, satellite data are considered not only as an instrument for recording spatial structure, but also as a means of revealing the hidden mechanisms underlying the functioning of the urban ecological system.

Additionally, open-access landscape plans and project descriptions of the parks were utilised, containing information regarding the location of water-retention elements, bioretention zones, bioswales, channels, retention ponds, and permeable surfaces. The use of such sources corresponds to contemporary research practices in the study of urban blue-green infrastructure and nature-based water management [10; 19].

The methodological framework of the research combines comparative case-study analysis with a quantitative assessment of stormwater-management potential based on land-cover structure. At the first stage, the territory of each investigated object was classified into three generalised categories: green surfaces, water surfaces, and impermeable artificial surfaces.

Green surfaces included lawns, trees and shrub vegetation, meadow landscapes, and wetland biotopes performing the functions of natural infiltration and atmospheric water retention. Water surfaces included ponds, canals, and river-channel sections participating in the regulation of territorial water balance. Impermeable surfaces - asphalt, concrete platforms, and other artificial coverings - were considered elements preventing the natural infiltration of water into the soil and contributing to increased surface runoff.

Such a methodological approach is widely applied in studies of Low Impact Development and Water Sensitive Urban Design, where particular attention is devoted to the integration of natural mechanisms regulating water flows within the structure of urban infrastructure [7; 20]. However, decisive importance lies not only in the quantitative analysis of surface coverage, but also in understanding the city as a unified hydro-ecological organism in which each surface element participates in the formation of microclimate, water circulation, and urban resilience. Such an integrated approach is increasingly applied in contemporary studies devoted to Blue-Green Infrastructures, where hydrological modelling combines surface runoff assessment, groundwater recharge analysis, and climate adaptation scenarios within a unified urban water-management framework [21]. Recent studies additionally emphasise the importance of long-term environmental monitoring and performance assessment within sustainable water-management systems. In particular, research devoted to groundwater remediation technologies demonstrates that the effectiveness of permeable reactive systems depends upon continuous hydrological evaluation, adaptive management strategies, and the quality assessment of ecological engineering materials [22].

For each surface category, the total area and proportional share within the territorial structure were determined, allowing for an assessment of infiltration and atmospheric water-retention potential. Runoff coefficients commonly applied in hydrological practice for different surface types were used for quantitative evaluation. The following values were adopted: 0.2 for green zones, 0.05 for water surfaces, and 0.8 for impermeable surfaces. These coefficients reflect differences in the ability of surfaces to infiltrate, accumulate, and discharge water and are widely applied in studies of urban hydrology. The total surface runoff was calculated according to the following formula [23-24]:

$$Q = \sum_{i=1}^{n} C_i \times A_i \tag{1}$$

where:

Q - conditional volume of surface runoff;

C_i - runoff coefficient for the i-th surface type;

A_i - proportional share of the corresponding surface within the territorial structure.

For each investigated object, the total site area, the proportion of green spaces, the area of water

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elements, and the share of impermeable surfaces were recorded. The obtained indicators made it possible to compare the water-retention potential of the investigated parks and to interpret the identified differences within the context of climatic conditions, spatial structure, and principles of urban organisation.

Spatial data processing was carried out using ArcGIS Pro, within which vectorisation of land-cover boundaries, area calculations, and land-use structure analysis were performed. Computational operations and statistical data processing were conducted in Python using the NumPy and Pandas libraries, ensuring the automation of calculations and reproducibility of results. The application of these tools corresponds to contemporary methods of spatial analysis and modelling of urban ecological systems [23].

The applied methodology ensures the reproducibility of the research, since it is based upon open-access data sources, standardised hydrological coefficients, and widely used software tools. Given the availability of comparable satellite imagery and information regarding land-cover types, the proposed analytical algorithm may be applied to assess the potential implementation of Sponge City principles in other urban territories, including public spaces, park systems, and ecological infrastructure elements within contemporary cities.

3 RESULTS AND DISCUSSION

The conducted comparative analysis of three implemented projects - Harbin Qunli Stormwater Park, Yanweizhou Park, and Bishan - Ang Mo Kio Park - made it possible to identify the key patterns underlying the integration of natural and engineering solutions within the framework of the Sponge City concept. The obtained results demonstrate that the spatial structure of green and water surfaces plays a decisive role in regulating surface runoff and forming sustainable urban ecosystems. In contrast to traditional engineering drainage systems oriented towards the rapid removal of water from the urban environment, nature-based solutions involve the temporary accumulation, infiltration, and natural filtration within the urban territory [1; 20].

One of the most illustrative examples of the implementation of this strategy is Harbin Qunli Stormwater Park in the city of Harbin. The park was created on the territory of a degraded wetland landscape covering approximately 30 hectares, which had previously been subjected to regular flooding during the monsoon season. The project, developed by Turenscape, represents a multifunctional nature-based engineering system incorporating a network of water bodies, wetland biotopes, canals, and terraced pedestrian pathways. The spatial structure of the park forms a circular system of hills and water reservoirs functioning as a buffer zone between the urban development and the central wetland core. The conducted land-cover analysis demonstrates that green vegetation occupies approximately 65% of the territory, while water elements account for around 15%. Calculations of conditional surface runoff based on infiltration coefficients indicate that the use of bioretention zones, permeable surfaces, and water-retention basins makes it possible to reduce the volume of surface runoff to approximately 35% during periods of intense precipitation (Figure 1).

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Figure 1 - Harbin Qunli Stormwater Park (Harbin, Heilongjiang Province, China) [25].

The landscape functions as a natural hydrological system, ensuring the retention and gradual redistribution of stormwater. The project received international recognition and was awarded several professional distinctions, including the ASLA Excellence Award (2012) and the International Architecture Award (2012), confirming its significance for the development of ecological urbanism [25].

Similar principles of nature-based design were implemented in Yanweizhou Park in the city of Jinhua. The park is located within a floodplain landscape at the confluence of three rivers and represents a system of adaptive spaces designed to accommodate periodic flooding. The spatial composition includes a network of canals, water reservoirs, and elevated pedestrian bridges connecting different parts of the park and ensuring its functionality even during rising water levels. The land-cover structure of the park is characterised by approximately 55% green areas, while water surfaces occupy nearly 20% of the territory. Such a configuration ensures the redistribution and temporary retention of stormwater runoff, thereby reducing pressure on the urban drainage system. In contrast to traditional hydraulic engineering structures, where water is regarded as a threat to urban infrastructure, in this project it becomes an integral component of the spatial composition and forms a new type of interaction between nature and the urban environment. The project additionally demonstrates that flood-adaptive landscapes, permeable surfaces, ecological terraces, and water-resilient public spaces can simultaneously perform environmental, engineering, and social functions within a unified urban ecosystem. Owing to its innovative approach to water-flow management and ecological restoration, the project was recognised as the World Landscape of the Year at the World Architecture Festival (2015) and is considered one of the most successful examples of Sponge City implementation [17]. (Figure 2).

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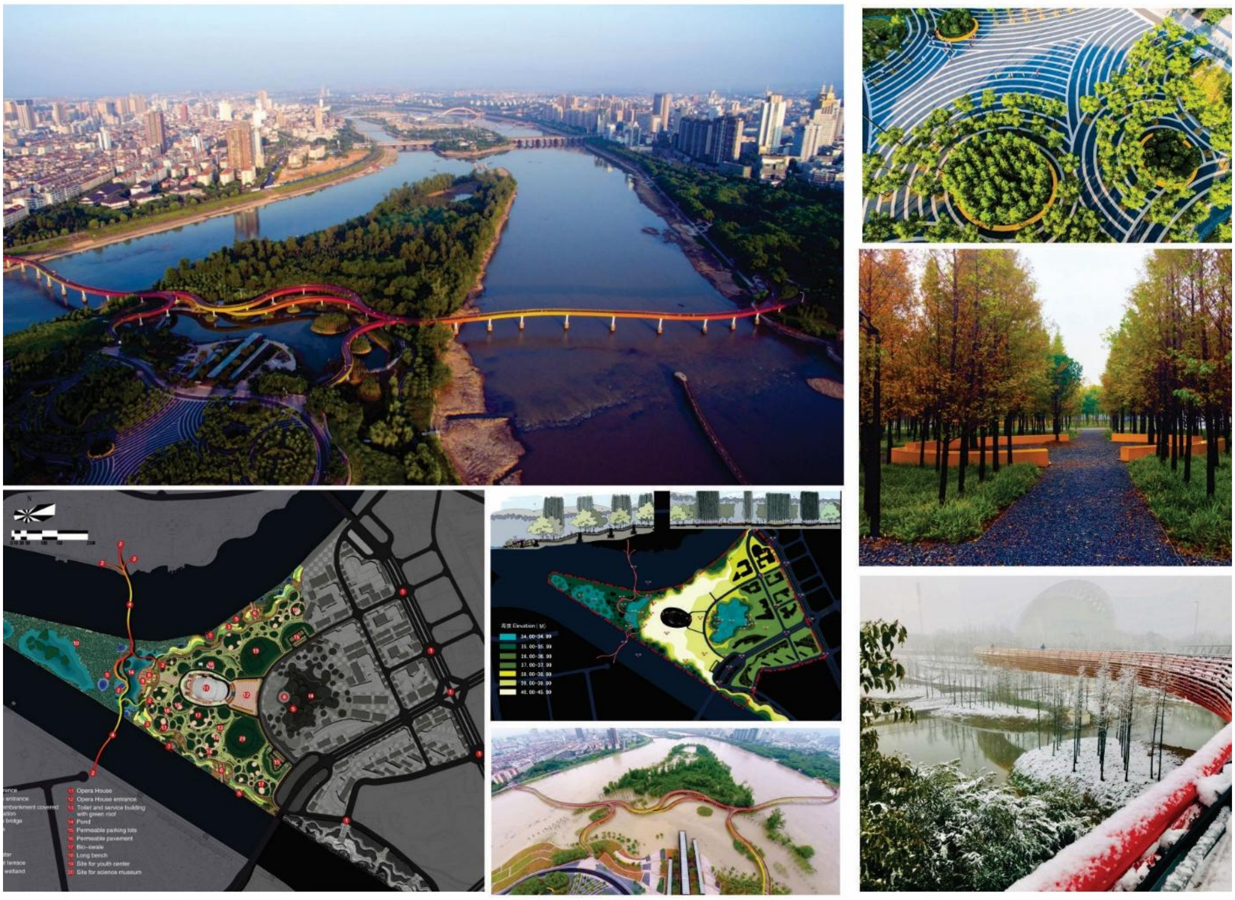

Figure 2 - Yanweizhou Park, Jinhua, Zhejiang Province, China [26].

Particular significance for the development of nature-based urbanism can be observed in the experience of Singapore, where the principles of integrating water and green infrastructure were implemented in Bishan–Ang Mo Kio Park. This project was implemented within the framework of the national ABC Waters Programme (Active, Beautiful, Clean Waters) initiative and became one of the largest examples of the transformation of traditional engineering infrastructure into a nature-based hydro-ecological system. During the reconstruction process, a 2.7 km concrete drainage canal was transformed into a meandering natural river channel extending 3.2 km and surrounded by a system of floodplain meadows and terraced riverbanks.

The total area of the park is approximately 62 hectares, with green zones occupying nearly 60% of the territory, while water surfaces and channels account for around 25%. Such a spatial configuration enables the retention of a significant proportion of stormwater runoff within the park and reduces peak pressure on the urban drainage system. In addition to its hydrological function, the project has had a substantial impact on the ecological condition of the territory. According to research conducted by the National University of Singapore, biodiversity within the park increased by more than 30% following the reconstruction, reaching approximately 197 species of plants and animals [27]. These results confirm the effectiveness of integrating natural and engineering solutions within conditions of dense urban development.

The project additionally demonstrates that water-sensitive urban design can simultaneously perform ecological, hydrological, recreational, and social functions within a unified urban ecosystem. Through the integration of naturalised river systems, flood-adaptive landscapes, soil bio-engineering techniques, and multifunctional public spaces, Bishan–Ang Mo Kio Park represents a successful model of environmentally adaptive urbanism in which infrastructure operates not as an isolated technical system, but as part of a living ecological framework capable of strengthening urban resilience and improving the quality of public space (Figure 3).

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Figure 3 - Bishan–Ang Mo Kio Park, Singapore [27].

A comparative analysis of the three case studies demonstrates that the effectiveness of nature-based solutions is largely determined by climatic conditions and the characteristics of urban structure. Within the tropical climate of Singapore, the higher proportion of water elements is determined by the intensity of precipitation and the necessity of redistributing substantial volumes of stormwater. In the northern regions of China, by contrast, an important role is played by bioretention zones and flood-resistant plant communities that ensure infiltration and natural water filtration. Despite these differences, all examined projects demonstrate a common tendency - the transition from traditional engineering drainage systems towards integrated blue-green infrastructures combining ecological, hydrological, and social functions [16; 23]. Recent studies further confirm that Sponge City implementation contributes to long-term urban climate resilience through the integration of adaptive hydrological systems, ecological infrastructure, and multifunctional public spaces into a unified urban framework [28]. To systematise the identified spatial, hydrological, and ecological characteristics of the examined case studies, a comparative evaluation of Sponge City nature-based solutions was conducted (Table 1).

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Table 1 - Comparative Evaluation of Sponge City Nature-Based Solutions and Their Contribution to Urban Resilience [Authors' material]

	Criteria	Harbin Qunli Stormwater Park	Yanweizhou Park	Bishan–Ang Mo Kio Park
1	Location	Harbin, China	Jinhua, China	Singapore
2	Climatic Context	Monsoon climate with seasonal flooding	Floodplain territory at the confluence of three rivers	Tropical high-precipitation climate
3	Key Sponge City Elements	Wetlands, retention basins, permeable surfaces, bioretention zones	Adaptive flood landscapes, elevated pedestrian bridges, reservoirs, and canals	Naturalised river channel, floodplain meadows, biofiltration systems
4	Green Surface Share	~65%	~55%	~60%
5	Water Surface Share	~15%	~20%	~25%
6	Main Hydrological Functions	Stormwater retention, infiltration, and natural filtration	Temporary water storage and runoff redistribution	Peak runoff reduction, river restoration, water purification
7	Ecological and Urban Benefits	Wetland restoration and microclimatic improvement	Ecological connectivity and adaptive public space	Biodiversity increase and blue-green transformation
8	Urban Resilience Contribution	Reduction of flood risks and adaptive landscape capacity	Flood-adaptive public infrastructure	Integrated climate-resilient water-sensitive urban system
9	Principal Lesson for Sustainable Urbanism	Nature-based wetland systems can effectively replace conventional stormwater drainage infrastructure.	Flood-adaptive public spaces can transform water-related risks into ecological and social assets.	Integrated blue-green infrastructure can simultaneously improve hydrological performance, biodiversity, and urban liveability.
10	Relevance for Kazakhstan	Applicable for urban wetlands and retention landscapes in Astana and Small Taldykol areas.	Relevant for flood-prone river corridors and adaptive public spaces in Almaty.	Applicable for the integration of blue-green infrastructure into densely urbanised districts of Almaty and Astana.

The comparative assessment confirms that, despite differences in climatic conditions and urban morphology, all analysed projects demonstrate the effectiveness of integrated blue-green infrastructure in improving runoff regulation, ecological resilience, and adaptive urban capacity. Nature-based solutions contribute not only to stormwater management but also to biodiversity enhancement, microclimatic improvement, and the formation of multifunctional public spaces within contemporary sustainable urbanism.

A comparison of the obtained results with findings from other studies indicates that the implementation of Sponge City elements can significantly reduce urban flood risks and increase the resilience of urban infrastructure to climate change [14; 16]. Furthermore, such projects generate additional ecosystem services, including microclimatic improvement, enhanced biodiversity, and the formation of high-quality public spaces.

The examined examples demonstrate that the Sponge City concept extends beyond the purely engineering tasks of stormwater drainage and becomes an instrument for shaping a new model of sustainable urbanism. Within this model, the city is understood as a dynamic hydro-ecological system in which natural processes are integrated into the structure of urban infrastructure and contribute to the formation of an adaptive, ecologically balanced, and socially oriented urban environment. Such a

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transition towards nature-based design models corresponds to contemporary architectural tendencies of the twenty-first century, in which innovative technologies, ecological principles, and cultural identity are regarded as interconnected components in the formation of a sustainable architectural environment [29].

The use of digital technologies for urban-environment design and analysis makes it possible to integrate ecological principles more effectively into architectural practice and to develop adaptive models of sustainable urbanism [30]. Furthermore, the study proposes a framework for the adaptation of Sponge City principles to the environmental and urban-planning conditions of Kazakhstan, with particular relevance for Almaty, Astana, and the Small Taldykol wetland system. The obtained results confirm that the integration of landscape and engineering solutions contributes to the formation of sustainable urban ecosystems and may serve as an effective instrument for adapting cities to the consequences of climate change.

4 CONCLUSIONS

The Sponge City concept represents a contemporary model of resilient and nature-based urban development, within which architecture, engineering infrastructure, ecological systems, and social functions are integrated into a unified urban organism. The analysed international case studies confirm that blue-green infrastructure can significantly improve the adaptive capacity of cities under conditions of increasing climatic instability and urbanisation pressure.

Approximately two decades after the active implementation of Sponge City principles in China and Singapore, the following conclusions can be drawn:

1. contrary to the traditional technocratic approach focused on the rapid removal of stormwater from urban territories, contemporary Sponge City projects demonstrate that water can become an integral component of ecological balance and spatial organisation within the city itself;
2. despite differences in climatic conditions and urban structure, all examined projects demonstrate a high level of efficiency in reducing surface runoff, improving ecological resilience, and enhancing the quality of the urban environment through the integration of natural and engineering systems;
3. the analysed projects demonstrate that nature-based infrastructure does not isolate urban territories from the surrounding urban fabric. Instead, it forms multifunctional public environments integrating recreational, ecological, hydrological, and social functions into a unified spatial system;
4. the implementation of green corridors, wetlands, permeable surfaces, bioretention zones, and adaptive water-retention systems contributes not only to flood mitigation, but also to biodiversity enhancement, microclimatic improvement, and the formation of sustainable public spaces attractive for residents and visitors alike;
5. the integration of landscape and engineering solutions within urban parks demonstrates that contemporary public spaces can simultaneously perform environmental, infrastructural, and social roles while maintaining a high level of spatial and functional quality.

The humane and sustainable characteristics of Sponge City environments can be identified as:

1. the integration of architecture, landscape, and hydrology into a unified ecological system;
2. the formation of adaptive and multifunctional public spaces;
3. the restoration of natural water-cycle mechanisms within the urban environment;
4. the improvement of ecological resilience and biodiversity;
5. the enhancement of urban comfort and environmental quality through blue-green infrastructure.

The examined projects demonstrate that resilient urbanism increasingly relies upon the harmonious interaction between natural processes and technological systems. Much like historical regional architecture adapted to climatic and environmental conditions, contemporary Sponge City strategies represent a new form of urban adaptation aimed at ensuring ecological balance, infrastructural resilience, and sustainable spatial development.

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This approach acquires particular significance for Almaty and Astana, the two largest cities of Kazakhstan, which face different but equally important environmental and infrastructural challenges. Almaty has historically developed under conditions of high seismic activity and a complex spatial structure dominated by low-rise private-sector development [31]. Astana, in contrast, is characterised by a sharply continental climate, strong winds, periodic water shortages, and rapid urban expansion. The integration of autonomous systems of water supply, energy, communication, and temporary life support into public spaces allows the urban environment to be understood as a unified organism, whose resilience depends not only on the structural stability of individual buildings, but also on the capacity of infrastructure systems to maintain continuity under crisis conditions.

The relevance of Sponge City principles is particularly evident in the case of the Small Taldykol lake system in Astana, which represents one of the most significant urban wetland ecosystems in Kazakhstan and provides important ecological, hydrological, and climate-regulating functions within the urban environment [32]. Historically functioning as a natural water-retention landscape, the area has played an important role in stormwater accumulation, microclimate regulation, biodiversity conservation, and the maintenance of ecological connectivity within the urban fabric. Contemporary discussions surrounding the transformation of the Small Taldykol territory illustrate the broader challenge of balancing urban development with the preservation of natural hydrological systems. In the context of increasing climate risks, including heat waves, extreme precipitation events, and urban flooding, the conservation and integration of such blue-green infrastructure elements may significantly enhance the adaptive capacity and environmental resilience of the city. The experience of Sponge City projects demonstrates that urban water bodies should be regarded not as obstacles to development but as valuable components of a sustainable and climate-responsive urban ecosystem.

From a practical perspective, the principles of the Sponge City concept may be applied in Kazakhstan through the preservation and restoration of urban wetlands, the creation of blue-green corridors along the Esentai and Bolshaya Almatinka river systems in Almaty, and the integration of water-retention landscapes into the development strategy of the Small Taldykol area in Astana. Such measures may contribute to reducing peak stormwater runoff, improving urban microclimate, enhancing biodiversity conservation, and increasing the long-term climate resilience of Kazakhstan's major cities.

Today, the Sponge City concept is regarded as one of the most promising directions in sustainable urbanism, integrating ecological principles, engineering technologies, digital analysis tools, and social needs into a unified model of adaptive urban development. The obtained results confirm that the future of architecture and urban planning is associated with the creation of flexible, resilient, and nature-oriented urban systems capable of preserving environmental and social stability under conditions of growing natural and technological uncertainty. The proposed recommendations may serve as a preliminary framework for pilot Sponge City implementation projects in Almaty and Astana.

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