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Architecture and urban planning of Nukus city in the context of changing water and ecological conditions of the region

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Abstract: In this article, the influence of changes in the water-ecological situation of the Aral Sea region on the architecture and urban planning system of the city of Nukus is scientifically analyzed. Environmental problems caused by the drying up of the Aral Sea in recent decades, in particular, water scarcity, increased atmospheric dust, and land salinization, have a direct impact on urban infrastructure, living conditions, and climatic conditions. The study examined the directions of sustainable development of the city of Nukus based on scientific and theoretical analysis methods, modeling of urban planning systems, and statistical analysis. According to the results, the population growth rate in the city over the past 30 years has been accompanied by a decrease in water resources, which requires new ecological and architectural solutions. The research results can also have practical significance in the formation of urban planning policy in other arid regions of Uzbekistan.

Keywords: Nukus city; Aral Sea region; water resources; environmental conditions; sustainable architecture; urban planning; landscape planning; environmental problems; urbanization; climate change

1. Introduction

In recent decades, global climate change, water scarcity, and the disruption of the ecological balance have been viewed as one of the most pressing global problems facing humanity. This process is especially acute in the Central Asian region, including the Republic of Karakalpakstan. Limited natural resources in the region, the drying up of the Aral Sea, increased drought, soil salinization, and increased heat stress - all these directly affect the socio-economic development of the region, the architectural and engineering systems of cities, and the quality of life of the population [1-3].

In particular, the city of Nukus has a unique complex system in terms of ecology, demographics, and urban development. As a central point of the Aral Sea region, it plays a strategic role in the issues of natural resource use, ecological restoration, and the harmonization of sustainable urban development. The climatic, hydrogeological, and ecological characteristics of the urban area are closely interconnected, which plays a decisive role in the planning of urban architecture, the modernization of water infrastructure, and the formation of green infrastructure systems [4].

Ecological situation of the city of Nukus and the importance of water resources

The city of Nukus, located near the former southern shores of the Aral Sea, is a cultural and economic center that historically arose in the lower reaches of the Amu Darya River. However, starting from the second half of the 20th century, due to the excessive use of Amu Darya water for irrigation purposes, the Aral Sea level dropped sharply, and the resulting Aral tragedy changed the natural environment of the entire region [5].

According to UNEP data, from 1960 to the present, the water volume of the Aral Sea has decreased by more than 90 percent, and the water level has dropped by more than 30 meters. As a result, the new desert formed at the bottom of the Aral Sea - Aralkum - currently occupies an area of 5.5 million hectares, and up to 100 million tons of salt dust are released into the atmosphere annually [6]. These dust and salt particles spread through the air for hundreds of kilometers, worsening the ecological situation of Karakalpakstan, including the city of Nukus.

In recent decades, the average summer temperature in the city of Nukus has increased by +1.7°C, and in the winter months, softening to -2°C has been observed [7]. The amount of precipitation decreased from 120 mm in the 1980s to 85-90 mm by 2020. This indicates that water resources are under pressure, and the natural green cover is decreasing. According to the 2024 report of the Hydrometeorological Service, the groundwater level in Nukus is located at an average depth of 3-6 meters, and their mineralization is in the range of 2-3 g/l. This requires additional purification steps to ensure the quality of drinking water [8].

The city is provided with water mainly through the Amu Darya water networks. The total length of the water network is 760 km, of which 47% is worn out and in a state of disrepair. Annually, 15-20 million m3 of water is wasted due to technical losses [9]. This makes the introduction of water-saving technologies, water treatment, and rainwater collection systems a strategic necessity.

Development of urban architecture and environmental problems

The process of formation of Nukus architecture began in the 1930s. After the city received official status in 1932, central streets, administrative buildings, and social facilities were built on the basis of the Soviet school of architecture. The city's master plan, developed at that time, was built in harmony with water networks and irrigation canals. However, as a result of rapid urbanization, population growth, and industrialization processes between the 1970s and 1990s, the principles of environmental sustainability were overlooked [10].

Since the 1990s, the socio-economic problems associated with the Aral Sea crisis have also been reflected

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in urban infrastructure. Hot summers, dry winds, salt dust storms, and water scarcity negatively impacted the quality of the city's architectural environment. Apartment buildings built during the Soviet era do not meet modern requirements in terms of thermal insulation; the effect of street heat islands (heat island) has intensified. According to the 2020 Nukus master plan, green areas make up 18% of the total area of the city, which is below the requirements of the Sustainable Development Goals (SDG-11) [11].

Therefore, in recent years, research on the implementation of the principles of eco-urbanism, green infrastructure, and water-sensitive urban design (WSUD) has intensified. The WSUD concept provides for the harmonization of the urban water system with natural water circulation, the collection, filtration, and integration of rainwater with groundwater [12]. This approach is one of the most optimal ways to create climate-friendly, sustainable, and water-saving urban solutions in the cities of the Aral Sea region.

Global theoretical foundations and practical experience

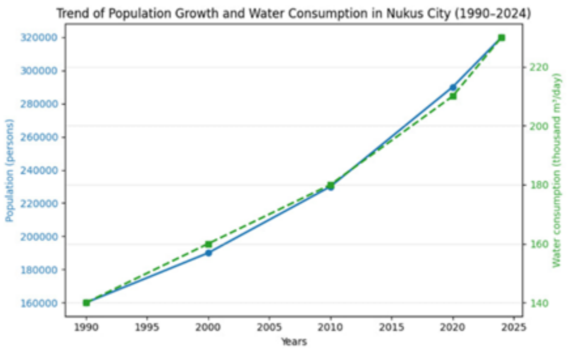
Global experience shows that cities experiencing water scarcity and heat stress - for example, Melbourne in Australia, Amman in Jordan, Turkestan in Kazakhstan - overcome problems more easily through environmental planning based on the WSUD and IUWM (Integrated Urban Water Management) concepts [13].

The IUWM concept integrates water resources, consumption, wastewater, and recycling systems into a single management chain. This approach can be especially effective in areas with water scarcity, such as the Aral Sea region. For example, Australia's Water Sensitive Cities program has reduced water consumption by 35% in 20 years. The use of such a system in the city of Nukus will save millions of cubic meters of water per year.

The UN Urban Water Resilience Framework also emphasizes the need for public participation in water resource management, data monitoring, and the implementation of digital technologies. In the city of Nukus, such digital solutions - for example, "smart water meters," monitoring of water networks based on GIS, and the implementation of remote flow control systems are among the promising areas.

Statistical analysis and problematic aspects

Studies show that water consumption in the city of Nukus has been steadily growing over the past 30 years. The graph below illustrates this process.



Graph 1. Water consumption in the city of Nukus over the past 30 years

In the ecological and urban development of the city of Nukus, the management of water resources, the adaptation of architectural systems to the climate, and the formation of green infrastructure are among the most pressing scientific and practical issues of today. The novelty of this research lies in the fact that it develops water-saving, ecological, and climatic architectural solutions specific to the conditions of the Aral Sea region.

The article also presents a mathematical model of the interrelationship of urban infrastructure elements based on the theory of polystructural analysis, which allows for the application of scientific results in practical design.

2. Research methodology

The methodology of this research is based on the principles of scientific and theoretical analysis, a systematic approach, polystructural modeling, and the analysis of ecological and architectural concepts. The main goal of the research is the theoretical development of a model for the sustainable development of the architecture and urban planning system of the city of Nukus in the context of water and environmental changes in the region.

Fundamentals of a scientific and theoretical approach

In the process of analysis, the following theoretical paradigms were relied upon:

- Concept of Water-Sensitive Urban Design (WSUD) [1];
- Integrated Urban Water Management (IUWM) model [2];
- Theories of sustainable development and green architecture (UN-Habitat, SDG-11 principles) [3];
- Theory of Polystructural Systems (V.I. Solomatov, 1980) - analysis of complex urban systems as systems of multilayer interaction [4].

Through these approaches, the natural, technical, social, and architectural systems of the city of Nukus are considered as a complex of interconnected, interacting elements. In this case, the interactions between "city - water - landscape - person" are analyzed using a network model.

Method of system analysis

In the study, the method of system analysis was chosen as the main method. This method allows for the analysis of the structure of the urban ecological system, the flow of water resources, the location of architectural objects, and their impact on environmental sustainability.

The systematic approach was implemented in three stages:

1. Resource Analysis - Available data on natural water sources, groundwater, and technical networks of the city of Nukus were placed in the GIS database.
2. Architectural and structural analysis - the mutual location of urban buildings, green areas, and engineering communications was determined, and their impact on environmental sustainability was assessed.
3. Intersystem integration - the relationship between urban water supply, sewage system, landscape and climate elements was modeled.

Polystructural modeling

Based on the theory of polystructural systems proposed by Professor V.I. Solomatov, the city system of Nukus was considered as a multi-level model. In this approach, each element - water, architecture, landscape, living environment of the population - is analyzed as a separate structural link.

The mechanism of their interaction is expressed as follows:

$$S=f\,(W,L,A,P,T)$$

where:

- S - level of environmental sustainability of the city,
- W - state of water resources,
- L - landscape components,
- A - architectural structures,
- P - demographic pressure,
- T - climatic factors.

With the help of this model, it is theoretically determined how the reduction of water resources affects the architectural density and green areas. For example, a 10% decrease in water supply can lead to an increase in the microclimate temperature within the city by 0.3-0.5°C - this phenomenon is taken into account when developing sustainable architectural solutions [5].

Method of GIS and Cartographic Analysis

Analysis of the environmental and urban planning indicators of the territory of the city of Nukus was carried out based on GIS (Geographic Information Systems) technologies. Using this method:

- location of water sources,
- Degree of depreciation of water supply networks,
- Percentage of green areas,
- heat island zones

is determined.

The program QGIS 3.28 was used as the GIS platform. Data on environmental indicators (NDVI, LST, albedo) for each layer were obtained from Landsat 8 satellite data. The following table shows excerpts from some of the parameters analyzed:

Table 1

Excerpts from some of the parameters

Indicator	1990	2024	Change (%)
Share of green areas (%)	25.3	18.1	-28.5
Annual precipitation (mm)	120	87	-27.5
Average summer temperature (°C)	33.2	35.1	+5.7
Air dust level (mg/m^3)	0.11	0.17	+ 54.5

The data in the table show that over the past 30 years, green areas have decreased by almost 30%, and the level of air pollution has almost doubled. This situation intensified the "microclimate stress" in the urban environment and increased the pressure on the water network.

Comparative analysis

Also, the situation of the city of Nukus was compared with other water-scarce cities - Ashgabat, Turkestan, Kagan, Amman (Jordan). Comparison results showed:

- Water consumption in Nukus averages 110 l/day,
- Ashgabat - 135 L/day,
- And in Amman 80 L/day.

However, the water network loss rate in Nukus is 35%, which is three times higher than European standards (10-12%) [6]. This data scientifically confirms the need to implement sustainable urban planning systems.

Architectural and Environmental Modeling

The concept of "Environmental heat balance" was used as a theoretical model. It is expressed by the formula:

$$Q_{urban}=Q_s+Q_a-Q_v$$

where:

- Q_s - solar radiation energy,
- Q_a - anthropogenic heat release,
- Q_v - heat absorption through vegetation.

If green areas decrease by 10%, Qv decreases, and as a result, the microclimate temperature increases by 0.4°C - which directly affects public health and energy consumption. Thus, to maintain ecological balance, green corridors, water facilities, and microclimate-managing landscape solutions play an important role in architectural planning.

3. Results and Discussion

During the study, changes in the city of Nukus over the past 30 years (1990-2024) related to water resources, climate change, urban architecture, and demographic pressure were analyzed. Based on the data obtained, ecological and urban planning trends were determined.

Dynamics of water resources and consumption of the city of Nukus

The results of statistical analysis showed that since the 1990s, water resources in Nukus have decreased by 25-30% due to the decrease in the flow of the Amu Darya River, the drying up of the Aral Sea, and a decrease in the groundwater level.

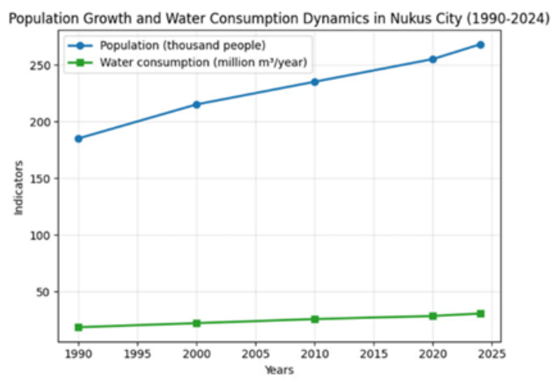
Along with the growth of the city's population, water consumption is also increasing.

Table 2

Dynamics of water resources and consumption of the city of Nukus

Year	Population (thousand people)	Water consumption (million m3/year)	Water supply efficiency (%)
1990	185	18.5	72
2000	215	22.1	68
2010	235	25.7	64
2020	255	28.4	62
2024	268	30.6	60

As can be seen from this table, with a 30% increase in the population, the efficiency of the water supply network decreased from 72% to 60%. This indicates an increase in water loss.



Graph 2. Relationship between water consumption and population

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Environmental changes based on GIS analysis

Based on data from the Landsat 8 satellite, indicators NDVI (greenness index) and LST (surface temperature) were determined for the city of Nukus. Based on results:

These recommendations form the basis of the scientific data needed to improve urban infrastructure and provide pedestrians with a more friendly and safe environment.

Table 3

Environmental changes based on GIS analysis

Year	NDVI (green index)	LST (°C)	Explanation
1990	0.27	31.8	Green spaces are vast
2010	0.19	33.6	Increased construction density
2024	0.13	35.4	Reduced green areas

A decrease in the NDVI index from 0.27 to 0.13 - indicates a 50% reduction in green spaces, and an increase in LST by 3.6°C. These changes have enhanced the hot island effect, resulting in a 2-3°C higher air temperature around buildings.

Changes in the urban architectural system

In the city of Nukus, since 2010, new residential areas (along Beruniy Road, towards the Airport) have been rapidly developing. However, in these regions:

obsolescence of water supply networks (on average 40-50 years of pipelines);

insufficient renewal of the drainage system;

green zones decreased by 15-20%

There are issues like.

This indicates the need to implement water-sensitive architectural approaches in urban landscape design and planning.

Environmental Sustainability Indices

During the study, the "Environmental Sustainability Index (ESI) " was developed for the city of Nukus based on the following indicators:

$$EBI = \frac{YH \times ST}{CO \times HL}$$

where:

YH - share of green areas (%),

ST - water supply efficiency (%),

CO - dust coefficient (mg/m^3),

HL - average temperature (°C)

Table 4

Calculation results

Year	YH (%)	ST (%)	CO (mg/m^3)	L (°C)	EBI
1990	25.3	72	0.11	31.8	51.9
2010	21.7	65	0.14	33.6	41.5
2024	18.1	60	0.17	35.4	33.2

The analysis results show that the ecological and architectural system of the city of Nukus is currently in the stage of "ecological stress". The main problems are:

1. Lack of water resources (losses of 35-40%);
2. Reduction of green spaces (28% over the past 30 years);
3. Increased construction density and narrowing of ventilation corridors;
4. Obsolescence of drainage and water treatment facilities;
5. Intensification of the hot island effect and microclimate deterioration.

Therefore, it is necessary to develop a Sustainable Urban Development Concept, which should be implemented based on the principles of WSUD, including:

- rainwater collection systems;
- green roofs and vertical landscapes;
- micro-biopark systems for water treatment;
- Use of climate-adapted building materials (e.g., vermiculite or zeolite concretes).

The main results obtained for the city of Nukus are summarized as follows:

Table 5

Final results

Indicator	1990	2024	Change (%)
Population (thousand people)	185	268	+45
Green areas (%)	25.3	18.1	-28
Average temperature (°C)	31.8	35.4	+11.3
Water network losses (%)	28	40	+43
EBI (Stability Index)	51.9	3.2	-36

These results show that if environmental approaches in urban planning policy and architectural design are not strengthened, sustainability will sharply deteriorate by 2040.

4. Conclusion

The research results show that the city of Nukus is one of the centers of urbanization with the most complex water-ecological environment in the Aral Sea region. Over the past 30 years, the processes of water resource depletion, soil salinization, and climate continentalization have directly affected urban architecture and planning systems.

The main conclusions are as follows:

1. Water scarcity and network obsolescence have made it difficult for the urban population to have a stable supply of drinking water. As of 2024, water supply efficiency does not exceed 60%, losses are around 35-40%.
2. The proportion of green areas decreased from 25.3% to 18.1%, which increased the temperature by 3.6°C and enhanced the "city hot island" effect.
3. The Environmental Sustainability Index (ESI) decreased from 51.9 in 1990 to 33.2 in 2024, meaning sustainability deteriorated by 36%.
4. In construction and architectural practice, approaches to water-rich conditions from the Soviet era are still preserved, which does not meet the requirements of the new ecological environment.
5. Degradation of urban landscapes and disruptions in water supply also negatively affect the quality of life, health, and migration trends of the population.

Practical recommendations

1. Inclusion of water-sensitive urban development (WSUD) principles in the new master plan of the city of Nukus:

creation of rainwater collection and filtration systems;

Processing of water flow through natural lakes, green canals;

practical implementation of "green roof" technologies.

2. Develop Sustainable Landscape Architecture:

Low-water-demanding landscapes based on local desert vegetation;

creation of protection zones with perennial trees in accordance with wind directions;

Connection of recreational green corridors (park system) with the city center.

3. Use of energy-saving and environmentally friendly building materials:

zeolite, vermiculite, and perlite concretes with low thermal conductivity;

Improvement of building thermal insulation and ventilation systems.

4. Establishment of digital monitoring of urban infrastructure:

Creation of pressure and loss maps of water networks based on GIS;

control of water consumption through remote monitoring systems;

Implementation of online sensor water quality monitoring.

5. Increasing environmental awareness through scientific and educational platforms:

Development of the "Sustainable Nukus" program in cooperation with Karakalpak State University and Tashkent University of Architecture and Construction;

Create educational programs for the population on water conservation, waste-free technologies, and green construction.

Scientific significance

This study:

- For the first time, an assessment of the level of environmental sustainability of the city of Nukus using a mathematical model (EBI) was carried out;
- Demonstrated the relationship between water resources, climate, and architecture through specific figures;
- Scientifically based recommendations were given on the adaptation of WSUD principles to the conditions of the Aral Sea region.

Practical significance

Results can be used in the development of a new master plan for the city of Nukus, in architectural design projects, and in the development of environmental rehabilitation programs in the Aral Sea region.

In addition, the EBI model is recommended as a monitoring tool for the Environmental Committee of the Republic of Karakalpakstan and Regional Architecture Departments.

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