The Role of Innovative Technologies in Reducing the Load on Wastewater Treatment Plants in the Cities of the Republic of Kazakhstan

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Abstract: - This article highlights an important aspect of modern management of urban wastewater treatment plants in the cities of the Republic of Kazakhstan, focusing on economic assessment of the effectiveness of integrated use of ecosystem solutions for surface (atmospheric) water collection. The study presents an analysis of the impact of such solutions on reducing the burden on wastewater treatment plants and optimizing operating costs. The authors consider different technologies and methods for surface water harvesting, including the use of green spaces, ecosystem elements, and innovative engineering solutions. The paper emphasizes the importance of considering economic aspects when deciding on the implementation of such ecosystem approaches. It presents examples of countries that have implemented, or are currently implementing integrated surface water management and the methods of ecosystem solutions that have shown the most positive ecological and economic effects after their implementation. In addition, the work considers and calculates the main components and concentrations of pollutants entering water bodies from urban areas. The authors conclude that the integrated use of ecosystem solutions for surface water harvesting is a promising approach that will not only reduce the burden on wastewater treatment plants but also contribute to the creation of more sustainable and cost-effective water management systems in the cities of the Republic of Kazakhstan.

Key-Words: - Ecosystem, atmosphere, ecosystem elements, water bodies, integrated management, treatment plants, surface (atmospheric) waters, concentrations of pollutants.

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1 Introduction

Water is one of the most important natural resources, both for human domestic needs and as a habitat for a wide range of organisms. However, population growth, industrial development, agricultural expansion, and infrastructure improvements are increasing the challenges of water supply. The effective management of atmospheric water is becoming increasingly important for the infrastructure of cities and for the safety of their inhabitants.

There are a number of problems with the sewerage system in Kazakhstan, particularly in the small towns and rural areas. This article highlights the main methods of atmospheric water disposal and analyses the status of the country's wastewater treatment facilities. It also presents methods of reducing the burden on wastewater treatment plants using innovative technologies. A lack of organized drainage of atmospheric water can lead to flooding of streets and disruption of traffic and pedestrian movement, as well as destruction of road surfaces and deterioration of sanitary conditions. It is therefore important to pay special attention to water management issues when planning and rebuilding urban and industrial facilities.

The drainage system in residential and industrial areas has evolved with the development of infrastructure and the improvement of local amenities.

Depending on the volume of wastewater and the organization's costs, one can choose different types of storm drainage. They include open, closed, and combined options. Open systems are outdoor networks of open channels with protective grates, often made of plastic or concrete, and are mainly used in pedestrian areas or on roads in historic city centers. Closed systems, on the other hand, involve the use of inlets and underground pipework and are recommended for large cities because of their durability and safety. Combined systems unite the advantages of both types. Depending on the connection and treatment requirements, connection to the systems can be centralized, local, or a combination of the two. In world practice, there are three types of surface wastewater harvesting: combined, separate and semi-separate systems, [1].

The original type of sewer system that was used in cities is combined. Nowadays, it is mainly used in historical parts of cities. It is characterized by the fact that all types of wastewater are discharged into a single sewerage network to a common treatment plant. During periods of heavy rainfall, water can be discharged into water basins to reduce the load on the system. However, this approach is not always in line with the principles of sustainable urban development and environmental safety.

Separate sewerage systems use distinct pipelines to segregate domestic, industrial, and rainwater sewage. There are two types of such systems: complete and incomplete. The main difference between them is whether the rainwater is treated or not.

In the case of an incomplete separate system, rainwater can be discharged directly into the water body through the ground or special holes in the pipes.

A semi-separate wastewater system is an infrastructure designed to collect and dispose of wastewater by combining rainwater and domestic wastewater into a single network for further disposal. Such systems may include elements of both a combined system (where rainwater and domestic wastewater are combined) and a separate system (where the sewers are separated). Semi-separate systems are often used in older sections of cities where limited space makes it difficult to create separate networks for rainwater and domestic wastewater collection, [2], [3].

In semi-separate storm drainage, domestic and industrial wastewater is combined into one collector, while rainwater is directed to a separate collector. This method helps to relieve the system during periods of heavy rainfall by separating the flow and improving the efficiency of surface water treatment. The system redistributes part of the precipitation to a collector with domestic and industrial wastewater through special separation chambers.

According to the Water Code and the Environmental Code of the Republic of Kazakhstan, it is prohibited to discharge untreated rainwater, snowmelt, and irrigation water from agricultural areas and enterprises into water bodies, [4]. The most polluted portion of surface runoff from rain, snowmelt, and road washing must be directed to treatment facilities. At least 70% of the annual runoff from agricultural land and similarly polluting industries, and all runoff from industries where hazardous substances or organic compounds may be used, should be directed to treatment facilities. If we calculate the capacity of treatment facilities for runoff from light, and frequent rainfall with an intensity period of 0.05 to 0.10 years, most settlements in the country meet these requirements.

When determining the conditions for discharging surface runoff from residential and industrial areas into water bodies, it is necessary to comply with the standards established by the legislation of the Republic of Kazakhstan for urban wastewater discharge. Where separate sewerage systems are used, surface water from the urban area should be treated at local or centralized treatment plants. Mechanical cleaning methods such as grates, sand traps, settling tanks, and filters are often used for this purpose. In some cases, it is possible to treat surface, domestic, and industrial wastewater together in a single treatment plant. During periods of minimal urban wastewater inflow, it is important to collect surface wastewater in tanks and direct it to the sewer system. In a semi-separated wastewater system, where surface water is mixed with domestic and industrial wastewater, the treatment process should follow the standard methods used for municipal wastewater. The load on the sewage treatment plant can be reduced by the use of regulating tanks. The choice of surface runoff diversion and treatment scheme and the design of treatment facilities should be based on qualitative and quantitative characteristics and discharge conditions, taking into account the technical and economic assessment of different options.

2 Hydrotechnical Support of Kazakhstan Cities: Analysis of Storm Drainage Systems, Precipitation Composition, and Seasonal Variations

2.1 Storm Drainage

Kazakhstan began building wastewater treatment plants in the 1950s. Since then, mechanical treatment plants have been put into operation in major cities. Previously, wastewater was disposed of in fields for filtration or discharged into water bodies. Since the beginning of the 1970s, the first sedimentation tanks have been built. To date, 62 of Kazakhstan's 89 cities have wastewater treatment plants.

According to a report by the Public Accounts Committee for 2019, the average level of wear and tear on sewer networks across the country was 52.2%. In some regions, including East Kazakhstan Region, Karaganda Region, and Pavlodar Region, this indicator is significantly higher than the average level. For example, in the cities of Kokshetau, Shalkar, Kapshagai, Semey, Ridder, Karatau, Saran, Arkalyk, and Ekibastuz, the level of wear and tear exceeds 90%.

The town of Taraz, in the south of the country, has no sewage treatment facilities, and waste water is dumped on fields to be filtered. In 2022, in response to the issue of deteriorating sewerage systems and treatment facilities, Kazakhstan suggested a project aimed at constructing and reconstructing sewerage systems in 53 cities across the country. This project will be financed using loan funds provided by the Asian Development Bank (ADB) and the European Bank for Reconstruction and Development (EBRD). The Ministry of Industry and Infrastructure Development of the Republic of Kazakhstan is responsible for its implementation.

Rainwater drainage systems are underdeveloped or non-existent in many cities in Kazakhstan. In particular, Almaty lacks engineering facilities to treat surface runoff, resulting in polluted water being discharged into rivers, including the Bolshaya and Malaya Almatinka, Esentai, Aschibulak, Terenkara, Aksai, Kargalinka, Kazachka and some smaller rivers, [5], [6].

In Astana, the stormwater drainage system consists of 18 treatment plants and one storage pond. The total length of the main collectors of the stormwater, drainage, and ditch sewerage network is 610.8 kilometers. These networks are designed to divert surface runoff from the territory of more than 16,700 hectares. Nevertheless, these measures prove to be insufficient. In this regard, in 2021, the local administration decided to implement the Road Map on the instructions of the head of state, which provides for the construction of stormwater drainage in the capital from 2021 to 2025.

The constructed wastewater treatment plants were commissioned in autumn 2022 and completed with landscape improvements in 2023. They are designed to treat rain and snowmelt water before it is discharged into the Esil River, replacing the previous direct discharge. As the structure is underground, a public garden has been created above and the area has been landscaped.

The problems with stormwater drainage in the special-purpose cities are indicative of the serious problems in the single-industry cities of Kazakhstan. For example, the city of Rudny has only 4.6 kilometerskilometers of storm water drainage, while the average annual volume of urban water runoff is 3,938,434.5 cubic meters, [7].

2.2 Waste Water Composition

Let us consider the composition of pollutants and their concentration entering water bodies from urbanized areas.

The composition of pollutants present in the surface runoff of residential areas includes:

– natural mineral and organic impurities resulting from absorption of gases from the atmosphere and soil erosion, including dissolved organic and mineral substances, as well as coarse particulate matter such as sand particles, clay, and humus;

– anthropogenic substances originating from various industrial enterprises, including petroleum products, road pavement components, heavy metal compounds, and other substances depending on the specialization of the local industry;

– bacterial contaminants that may enter drains when the sanitary condition of the territory and sewerage networks is not satisfactory and when maximum flow rates are exceeded.

The qualitative and quantitative compositions of surface runoff are affected by:

– degree of area improvement;
– traffic intensity;
– population density.

The composition of surface runoff, including various elements such as suspended solids, BOD20, and petroleum products, is a key factor in selecting the optimal treatment technology, according to the Recommendations of the Construction Regulations of the Republic of Kazakhstan 4.01-03-2011 Water Drainage. Outdoor networks and structures on the surface of residential areas, [8], [9]. These parameters vary depending on various conditions, such as the level of landscaping, road surface cleaning, the presence of main streets with heavy traffic, adjacent industrial facilities, and the degree of contamination of roofs of buildings and structures.

The amount of surface runoff from residential and industrial areas during rainfall, snowmelt, and street washing in each city in Kazakhstan varies depending on the amount of rainfall in different seasons, surface characteristics, and the volume of the watercourse. Figure 1 and Figure 2 show a graph of the approximate composition of surface runoff of rain and snowmelt water from residential areas.

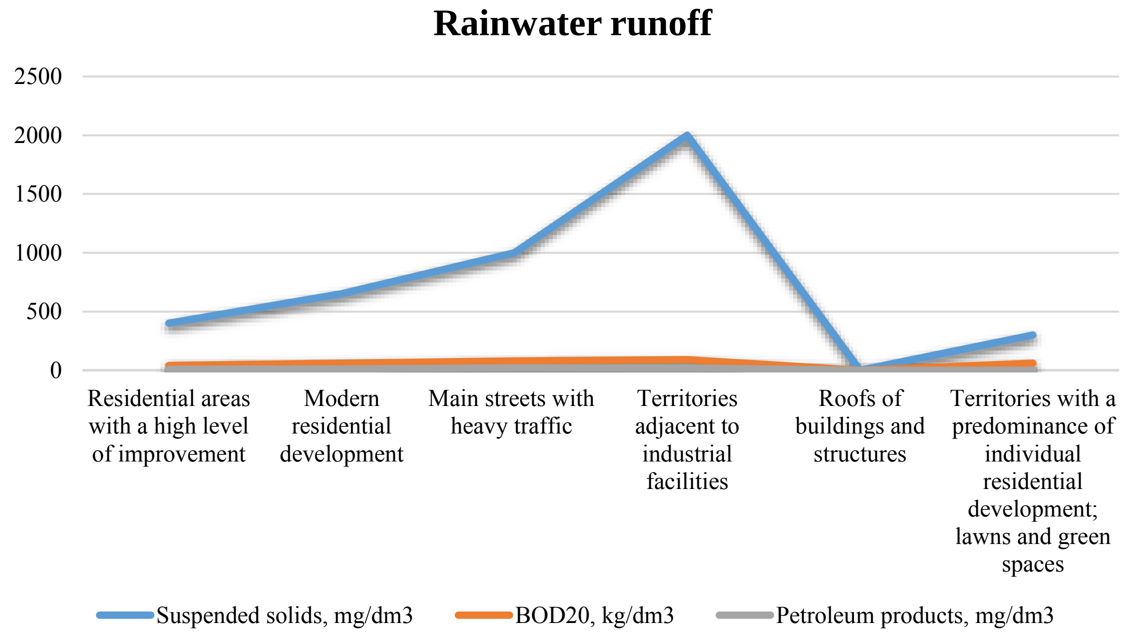

Fig. 1: Content of pollutants carried by rainwater runoff from residential areas

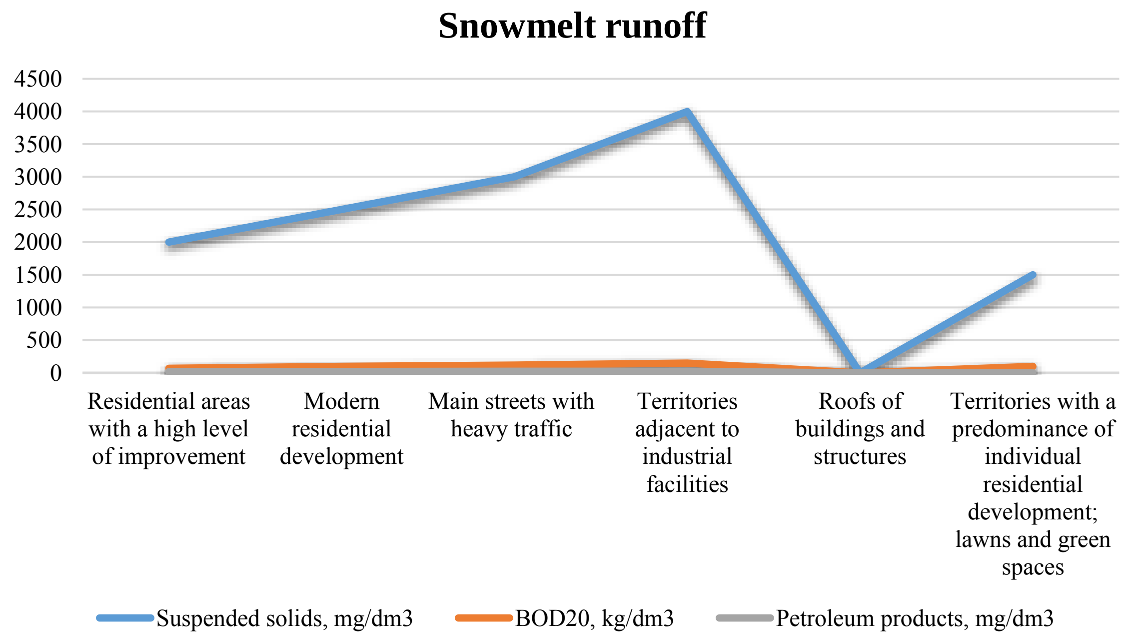

Fig. 2: Content of pollutants carried by snowmelt runoff from residential areas

The graphs show that significant excesses of the MPC for pollutants exceeding the norms during the formation of surface water flow are suspended substances. The largest quantities are found on main streets with intensive traffic and areas adjacent to industrial facilities.

Usually, the highest values of these indicators are characteristic of meltwater, which can be comparable to untreated domestic wastewater in terms of BOD_{20} content.

Surface runoff from urban areas can lead to pollution and contamination of river and lake waters that serve as a source of drinking water and recreational areas and leads to an intensification of the flooding process in urbanized areas.

When pre-treating rain and snowmelt water, the effect of reducing the concentration of suspended solids and petroleum products by delaying the flow in the storage tank for 1-3 days can reach 80-90%, whereas the concentration of dissolved organic matter will be reduced by 60-80% for BOD_{20} and by 8-90% for COD. Due to the high content of fine impurities in the surface runoff with hydraulic size less than 0.2 mm/s, the concentration of suspended solids in the residual water may vary from 50 to 200 mg/dm^3, whereas the concentration of petroleum products varies from 2 to 10 mg/dm^3 from residential areas and up to 10-50 mg/dm^3 from industrial sites. The residual content of dissolved compounds in terms of COD and BOD_{20} may be 50-100 and 20-30 mg/dm^3 respectively, [10].

2.3 Seasonal Variation of Precipitation

Due to climate change, the Republic of Kazakhstan is experiencing changes in the seasonal precipitation pattern. These changes may vary from region to region, but in general, they have an impact on water resources and ecosystems.

On average, precipitation in Kazakhstan is above the norm in spring and autumn - 113.6% and 112.2%, and below the norm in winter and summer - 92.8% and 78.4%, respectively. In winter 2021/2022 (December 2021 - February 2022), the average winter precipitation in Kazakhstan was 92.8 % of the norm. In the most part of the country, precipitation was more than 80 % of the norm, which is shown in Figure 3.

The largest amount of precipitation (more than 120% of the norm) was recorded in the western regions of the country (122-187%), in the northern regions (124-176%), and in some southern areas (122-134%). Particularly significant excesses of the norm were noted at the meteorological stations of Zhetykonur in the Ulytau region (165%) and Karauyl in the Abay region (196%). These indicators, as well as data from a number of meteorological stations in the Kostanay and Atyrau regions, allow characterizing the winter season in these regions as "extremely wet".

At the same time, in the Mangistau region (33-71%), southern regions (41-79%), Karaganda region (55-79%), in the east of the country (55-79%), and in some north areas (44-78%) there was a deficit of precipitation, which led to extremely dry conditions in a number of territories.

The spring season of 2022 also brought interesting changes: on average, precipitation in Kazakhstan was 114% of the norm. The precipitation excess was especially felt in the western and southern regions, with the exception of the Kyzylorda region. In the western regions, precipitation was twice as high as normal, reaching 204-280%. In the southern regions of Turkestan, Zhambyl, Almaty, and Zhetysu regions, significant excess precipitation was also recorded (122-195%), as at the Aral Tenizi weather station in the Kyzylorda region (179%).

In the spring of 2022, new precipitation records were set, including 270.7 mm at the Zhalanash weather station in the Almaty region and 151.1 mm at the Chapayevo weather station in the West Kazakhstan region. Nevertheless, precipitation deficits continued to prevail in the north and east of the country, where the amount was only 26-79% of the norm.

Insufficient precipitation was also observed in some areas of the Kyzylorda and Karaganda regions, confirming the complex climate dynamics in Kazakhstan in recent years.

The summer and autumn seasons in Kazakhstan showed significant changes in precipitation patterns, which are part of the overall climate dynamics in the country.

In summer, the average precipitation across the territory was only 78% of the norm, indicating a dry season with a 13% probability of below-normal precipitation. Most of Kazakhstan's territory experienced a precipitation deficit, with some regions experiencing precipitation below 80% of the norm. Particularly dry zones (less than 20% of the norm) were recorded in Mangistau (only 9% of the norm), Aktobe (15%), Kyzylorda (15-18%), and Turkestan (12-15%) regions. A new minimum of only 82.7 mm of precipitation was recorded at the Narynkol weather station. In some parts of the country, conditions were so extreme that they could be described as “extremely dry”. Only in certain regions of the western (136-276% of the norm), southern (137-274%) and northern (128-156%)

parts of the country there was excess precipitation, [11].

Autumn, on the contrary, brought more moisture. The average level of precipitation across Kazakhstan was 112% of the norm. In the northern regions, such as Kostanay (122-190%), North Kazakhstan (121-145%), and Akmola (126-162%) regions, there was a significant excess of precipitation. In the western part of the country, including West Kazakhstan (132-188%) and Mangistau (155-198%) regions, there was also an excess of moisture. The southern regions did not remain on the sidelines: in the Kyzylorda region, the amount of precipitation reached 211% of the norm, in Turkestan - 140-277%, in Zhambyl - 133-167%, in Almaty - 136-191%, in Zhetysu region - 130-178% of the norm. As a result, according to data from sixteen weather stations located in the western, southern, and northern regions, autumn 2022 was marked as “extremely wet”, [12].

Snow cover is an important climatic factor. Observation and study of snow cover is important for various types of economic activities. The great length of Kazakhstan's territory and a variety of physical and geographical conditions determine different humidity and snow cover conditions. Kazgidromet Republican State Enterprise carries out observations of snow cover at meteorological sites and on snow measuring routes and also uses remote sensing methods (RS).

Changes in snow cover characteristics were analyzed using NASA FEWS NET Land Data Assimilation System (FLDAS) data. The system provides open access to a set of snow cover characterization products. The products have a daily update period, spatial resolution of 1 km, and an archive since 2000. Among the most informative products for the conditions of Kazakhstan are: Daily Snow Depth, Daily Snow Depth Anomaly, Snow Water Equivalent, and Daily Snow Water Equivalent Anomaly. Average values of snow cover characteristics for the region(s) are based on calculations using data determined on a regular grid with a step of 1 km.

The pattern of the average snow depth during the cold period (November - April) of the season 2021/2022 and for the previous cold period 2020/2021, averaged over the territory of Kazakhstan as a whole is presented in Figure 4. Spatial distribution of the daily snow depth pattern in Kazakhstan in the 2021/2022 season as of 21-31 March 2022.

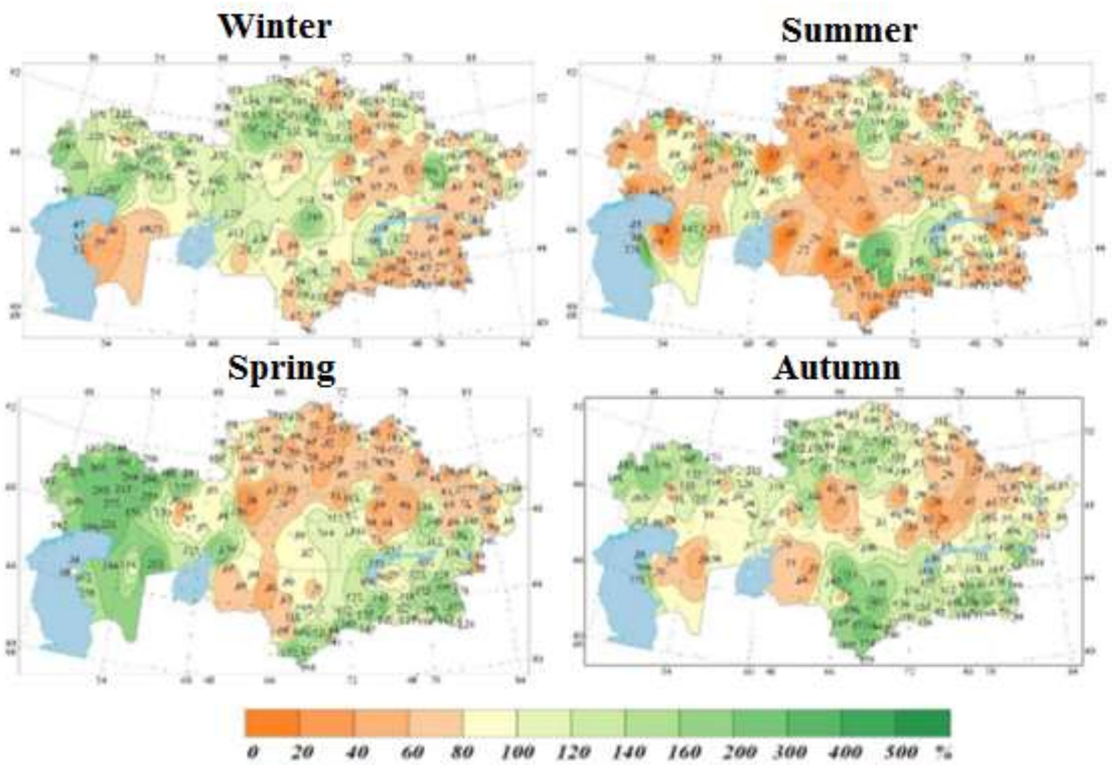

Fig. 3: Geographical distribution of seasonal precipitation in Kazakhstan in 2022, in % of the norm for the base period 1961-1990

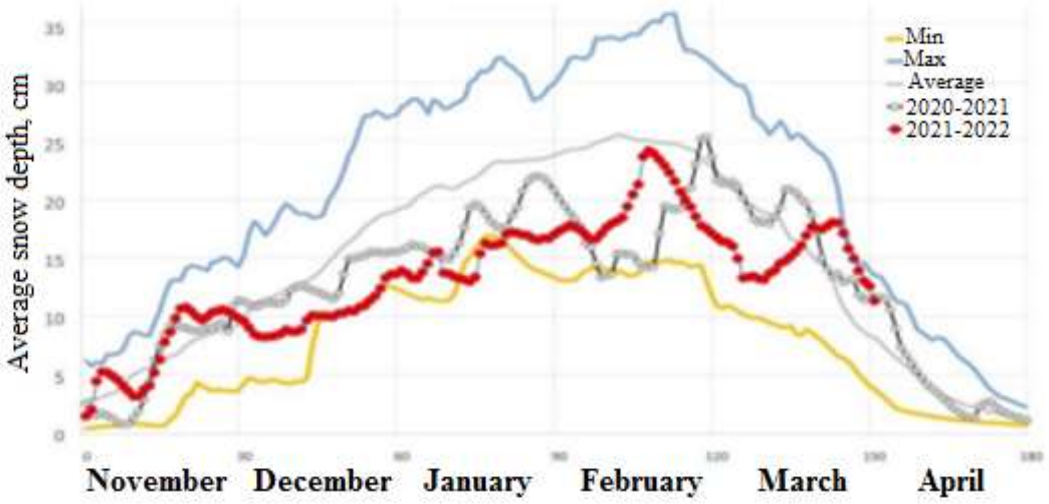

Fig. 4: Average snow depth pattern

Table 1. Ten-day values of share (%) of snow coverage in the regions of Kazakhstan and its changes for the period from 31 December 2021 to 31 March 2022. to 31 March 2022

Region	31/12	10/01	20/01	31/01	1002	20/02	28/02	10/03	20/03	31/03
Kazakhstan	83	83	90	92	92	84	75	71	81	58
West Kazakhstan	100	100	100	100	100	100	79	98	100	49
Atyrau	86	73	100	100	100	57	27	42	92	0
Mangystau	8	14	38	38	29	0	0	5	12	0
Kostanay	100	100	100	100	100	100	100	100	100	100
Aktobe	81	98	100	100	100	96	88	90	100	78
Akmola	100	100	100	100	100	100	100	100	100	100
North Kazakhstan	100	100	100	100	100	100	100	100	100	100
Pavlodar	100	100	100	100	100	100	100	96	100	89
Karaganda	100	100	100	100	100	100	100	91	100	66
East Kazakhstan	100	100	100	100	100	100	100	98	100	90
Turkestan	49	42	42	54	56	42	26	11	28	11
Kyzylorda	61	52	79	95	84	51	30	12	42	0
Almaty	77	71	79	91	98	93	70	6	61	30
Zhambyl	42	45	58	80	78	63	33	42	46	9

Note: Kazgidromet materials, [11]

Table 1 presents ten-day values of the share (%) of snow coverage in the regions of Kazakhstan and its changes for the period from 31 December 2021 to 31 March 2022.

During the spring and autumn seasons, the average amount of precipitation across the country is above normal, indicating a tendency for wetter conditions during these periods. In contrast, the winter and summer months are characterized by a deficit of precipitation, especially in summer, leading to dry conditions in some regions.

The most notable deviations from the norm are observed both increasing and decreasing in precipitation. In some regions, such as the western and southern regions, precipitation is significantly above normal, leading to extremely wet conditions that may pose additional challenges to water management and agriculture. On the other hand, in some parts of the country, particularly in the south and west, extremely dry conditions are observed, with precipitation significantly below normal, increasing the risk of droughts and reducing water availability.

Changes in seasonal precipitation patterns can entail various challenges such as water management, dealing with droughts or excessive precipitation, and adapting agriculture to new conditions.

Analyses of the quality of surface wastewater collected in large cities have revealed a high level of pollution. The degree and nature of this pollution depend on several factors, including the sanitary condition and the level of improvement of the territory where the wastewater is collected. Precipitation, its intensity and duration, droughts and the intensity of snowmelt have the greatest impact. The amount of pollution entering surface runoff water depends on the population, the degree of landscaping, the frequency of street cleaning and watering, and the condition of road surfaces. As the number of cars on city streets increases, there is an increase in the pollution of rain and meltwater runoff with petroleum products.

As the history of major spring floods in Kazakhstan and around the world shows, they can cause major flooding, destruction of irrigation systems, breaches of dams, levees, and other hydraulic structures, and millions of tenges in damage. Breakthroughs destroy houses, households, and industrial buildings, and can even lead to loss of life.

Over the past decade, our country has experienced many large, destructive floods.

In 2011, 38 settlements in five districts of the West Kazakhstan region were flooded, 2,600 residential houses, 7,146 summer houses were damaged, and hundreds of cattle fell.

In 2012, 23 settlements in nine districts of the South Kazakhstan region were flooded, affecting 254 houses and a thousand private farms.

In 2013, the dam of the reservoir in Kokpekty village of Bukhar-Zhyrau district of the Karaganda region burst due to a sharp inflow of meltwater.

In 2014, flood waters came to 13 settlements located in five districts of Akmola region, flooding about 430 residential houses.

In 2015, the regional center, the cities of Temirtau, Shakhtinsk, and almost 50 settlements, and two wintering areas in nine districts of Karaganda region were flooded. More than 170 out of 1,120 flooded houses were destroyed, a large number of livestock fell.

In 2017, large floods occurred in North Kazakhstan, East Kazakhstan, Almaty, Zhambyl, Kostanay and Aktobe regions.

In 2018, a similar situation occurred here. In East Kazakhstan alone, the damage totaled KZT 2,205,000,000.

In May 2020, due to heavy rains, the dam of the Sardoba reservoir in Uzbekistan burst, bringing a large flood to the Maktaaral district of Turkestan region.

In 2022, 185 dwellings were flooded by meltwater in Aktobe, West Kazakhstan, Pavlodar and Karaganda regions.

Meanwhile, according to Kazgidromet, the area of Kazakhstan covered with snow is 72%. By analyzing the values of precipitation, water reserves in snow, autumn soil moisture, soil freezing depth, as well as the ice conditions of rivers, one could give a preliminary assessment of flood-prone regions. These include, first of all, ten regions: Karaganda, Akmola, North Kazakhstan, Kostanay, Aktobe, West Kazakhstan, East Kazakhstan, Abay, Almaty and Zhetysu. The remaining seven are in areas with medium and low risks.

As shown by long-term observations at weather stations, in March and April a monthly norm of precipitation can fall in a day, which can lead to the occurrence of dangerous natural hydrometeorological phenomena, Figure 5.

Fig. 5: Flooding of houses

Working with statistical data for Kazakhstan it is possible to propose new technologies and methods of surface water harvesting, including the use of green spaces, ecosystem elements, and innovative engineering solutions.

3 Ecosystem Elements and Innovative Engineering Solutions

In the context of a changing climate, it is becoming increasingly urgent to review and find optimal methods of water utilization and stormwater management. Stormwater flows, mixed with rubbish, heavy metals, and other pollutants, pose a serious problem requiring immediate intervention. Green infrastructure such as green roofs, permeable pavements, bioswales, rainwater harvesting systems, green alleys, stormwater parks, and reserves effectively counter stormwater pollution and reduce flood risk while providing open spaces for recreation and living, improving air quality, regulating climate and contributing to an attractive environment.

3.1 Rain Gardens

Rain gardens are an important component of a sustainable stormwater management system, helping to reduce the load on main sewer systems and making landscapes aesthetically pleasing.

In various countries around the world, such as the US, UK, Australia, and Ukraine, as well as in northern regions including Norway, Sweden, and

Finland, rain gardens are widespread and utilized as an important element of sustainable urban development. Rain gardens play a key role in such programs as Environmental Stormwater Management (ESM) and Low Impact Development (LID) in the US, Sustainable Drainage Systems (SuDS) in the UK, and Water Saving Urban Design (WSUD) in Australia.

However, in countries with northern climates characterized by low winter temperatures and significant snowfall, rain gardens need to be adapted to the local weather conditions and use plants that are well adapted to the local environment.

To create a rain garden in Kazakhstan, the following shrubs and herbs can be used to "drink" excess water, facilitating the work of urban drainage systems, [13]:

A combination of different types of plants and shrubs can give a rain garden diversity, beauty, and functionality. Here are some idea combinations:

Elderberry and Lavender:

Elderberry will provide height and texture to the garden and attract birds and insects. Lavender adds fragrance and color to the garden and is a source of nectar for bees and other beneficial insects.

Verbena and Melissa:

These plants love moist conditions and attract butterflies and other beneficial insects. Verbena, with its bright flowers, creates a beautiful backdrop, while melissa adds fragrance and texture to a rain garden.

Virginia Cypress and Lily of the Valley:

Virginia cypress will give the garden structure and a green backdrop, while the lily of the valley with its fragrant flowers will beautify the garden and add notes of delicacy.

Silverberry and Almond:

Silverberry, with its beautiful autumn foliage, will create interesting contrasts in your garden throughout the year. Almond, with its fresh fragrance and green leaves, enhances the beauty of the silverberry and adds an extra element of decoration.

Willow and Daylily:

Willow, with its curved branches, will create a cozy space in the rain garden and protect it from the wind. The daylily, with its bright colors, and flexible leaves, will add elegance and charm to a rain garden.

These combinations can only serve as a starting point. It is important to consider local conditions, water availability, and lighting when selecting plants and shrubs for a rain garden, [14], [15].

As well as being aesthetically pleasing, rain gardens remove coarse pollutants by filtering runoff through the load, providing up to 95% removal of suspended solids. As many heavy metals and petroleum products are associated with suspended solids, their concentrations are also reduced by the removal of coarse impurities.

Sorption and ion exchange processes on the filter media particles remove dissolved substances in the surface runoff. Biological absorption, decomposition, and binding of pollutants by plants and biofilm, which is formed in the filter media and on plant roots, play an important role in treatment. During dry periods, the ultraviolet part of the sun's rays helps to break down trapped organic compounds and also has a disinfectant effect. The main mechanisms for the extraction of dissolved impurities in rain gardens are shown in Figure 6.

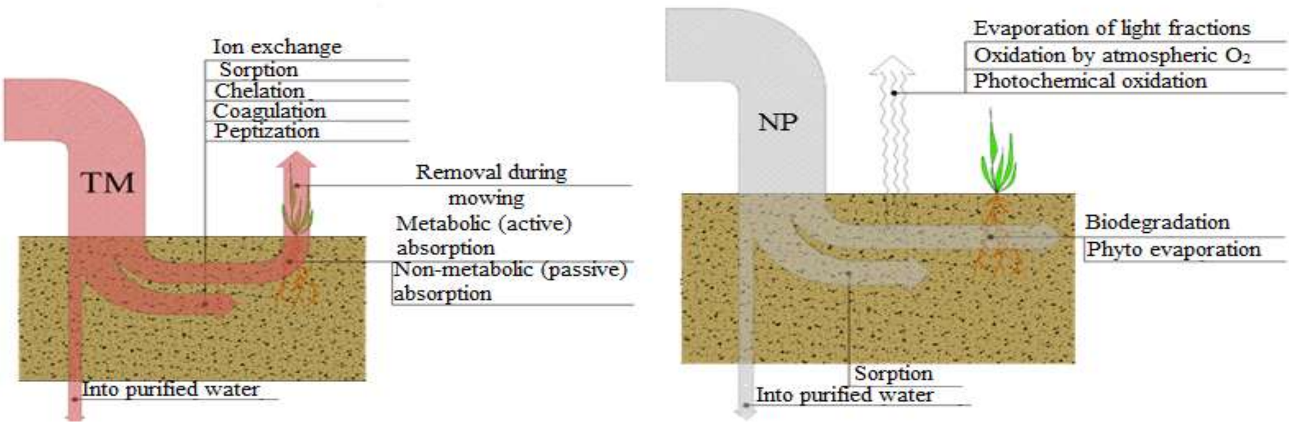

Fig. 6: Main mechanisms of dissolved impurities extraction in rain gardens
Scheme of dissolved impurities extraction in rain gardens

The combination of the described processes provides high efficiency in the removal of various pollutants: petroleum products: at the level of 90%, organic substances (by BOD): at the level of 70%, zinc, lead, and cadmium: at the level of 90%, copper: at the level of 80%. Total nitrogen removal is 75%, nitrite and nitrate removal is 80% and phosphorus removal is 90%. However, under certain conditions, nitrogen and phosphorus can be released from organic debris and dead plant parts, which can increase their initial concentration in runoff after passing through the rain garden.

To improve the efficiency of removing dissolved pollutants from water, rain gardens can use fillers with high sorption and ion exchange activity, such as zeolite, vermiculite, perlite, and activated carbon. These materials have unique properties that help improve the quality of water filtration and purification. Zeolite, a natural mineral with high porosity, is able to effectively absorb and retain various pollutants. Due to its ion exchange properties, zeolite can replace harmful ions, such as ammonium and heavy metals, with less dangerous analogs. Vermiculite, a layered mineral, is able to absorb water and hold various pollutants in its layers. It also helps retain moisture in the rain garden, which improves conditions for biological processes and regulates soil moisture. Perlite, a lightweight and porous material, helps improve water filtration. Its structure allows for the even distribution of water across the entire surface of the rain garden, increasing the interaction of water with other fillers, which increases the overall efficiency of the treatment system. These materials significantly reduce the concentration of harmful substances in surface runoff, preventing environmental pollution, [16]. In moderate climates where cold temperatures can slow down biological cleaning processes, these media provide reliable filtration and contaminant absorption, maintaining the effectiveness of the rain garden. Due to their properties, media reduces the load on the soil and plants, which helps prevent clogging and degradation, ensuring long-term and stable operation of the system.

3.2 Water Permeable Pavements

The rapid increase in the use of impermeable building materials in transport infrastructure and agricultural construction reduces the infiltration of rainwater into the soil. In a natural ecosystem, water evaporation is 73%, exceeding runoff and leakage, but in urban environments, outflow (55%) dominates compared to evaporation and leakage. There is therefore a need to develop water management systems in the construction industry. One method of addressing this problem is the use of water-permeable concrete pavements.

Water permeable concrete was introduced back in the 1980s and has been successfully used in various areas including the US, Japan, Western Europe, and Scandinavian countries due to its many advantages. Today, this material is widely used in the construction of private roads, car parks, footpaths, pavements, courtyard driveways, cycle and pedestrian paths, golf courses, and other facilities, Figure 7.

Currently, this construction material continues to attract the attention of many research centers around the world. In fact, the same base materials are used to produce permeable concrete as for conventional concrete, except that fine aggregate is often eliminated completely and the dosage of coarse aggregate (crushed stone, gravel) is carefully adjusted to improve curing properties. The result is a mix that requires special skills in mixing, placing, compacting, and curing. Although the water-repellent properties of this concrete mix are slightly inferior to those of conventional concrete mixes, the dosage of all components must be strictly controlled to achieve the desired results.

Fig. 7: Footpaths

The use of permeable concrete primarily reduces the drainage of water into the sewerage system, thereby naturally recharging the water table and, as a result, eliminating pollutants such as hydrocarbons, de-icing agents, oils, fuels and lubricants, which pollute river basins and damage the ecosystem, as in the case of artificial rainwater harvesting and mass discharges into watercourses (research shows that 97-99% of oils injected into permeable concrete are captured and naturally biodegraded), Figure 8.

Fig. 8: Application of permeable concretes

The tiles with the highest permeability have an appearance similar to that of popcorn. Uniformly distributed aggregates of the same size, used in close proximity, produce concrete with open voids that promote rapid drainage of large volumes of water. Some people like the natural, rough look of plain permeable concrete. However, there are several ways to improve its aesthetics for those who prefer a different style. Improvements can include coloring, stamping, jointing, and grinding.

Water-permeable concrete is a more economical option for pavement construction, Figure 9. Pavements made from this material have lower initial construction costs because there is no need for a rainwater drainage system, reducing the cost of installing underground pipes and gutters, [17]. In addition, there is no need to invest in land for the construction of retention ponds or filtration systems. As a result, land owners can utilize the surrounding area much more efficiently.

Fig. 9: Water permeable concretes

However, pavements made of permeable concrete can withstand significant loads exceeding 20 MPa, i.e. they are strong enough for the possible entry of a fire truck or heavy construction equipment. If these loads are not intensive, there will be no damage to the road surface. From the driver's point of view, the texture of permeable concrete pavements also has advantages. When driving in difficult weather conditions such as rain or snow, permeable concrete improves road safety. Rain and snow melt are absorbed into the concrete and do not remain on the surface, eliminating water accumulation and significantly reducing the risk of aquaplaning on wet roads, [18], [19].

4 Application of Ecosystem Approaches in Countries: Experience and Methodologies

The London Transport Strategy 2018 sets a target of reducing impervious surfaces by more than 5 hectares annually. In addition, the city is actively educating residents on the implementation of SUDS elements: developing guidelines and providing grants for residents and communities wishing to utilize SUDS on their sites.

In Sydney, the domestic and storm sewer systems operate separately. Half of the stormwater system is managed by Sydney Water and the other half is managed by the city's municipalities. Landowners are responsible for managing stormwater on their properties, [20].

As part of the Sydney 2030 strategy, an Environmental Action 2016-2021 Strategy and Action Plan has been developed. The document envisages connecting various facilities and parks to alternative sources of water supply, including rainwater harvesting, as well as upgrading park irrigation systems, introducing rain gardens, and replacing impermeable pavements with green spaces, [21].

Among the implemented projects, the Green Square Stormwater Drain Project is noteworthy. This project created a 2.5-kilometer-long surface runoff drainage system equipped with 1,800 mm diameter pipes and used green infrastructure to clean the runoff from debris. After treatment, the water is collected in tanks under the Matron Ruby Grant Park and then piped to the residences for use in flushing toilets and watering plants.

Sydney has also introduced a system of rates for surface water drainage services depending on the type of property. There is a flat fee for residential property owners, which varies by property type. For example, owners of single-family homes pay a rate of AUD 20.78 per quarter and flat owners pay a rate of AUD 6.64. Table 2 shows the stormwater disposal rates for residential properties in Sydney, Australia, for 2021-2023, [22].

Table 2. Stormwater rates for residential properties in Sydney, Australia, for 2021-2023.

Type of property	Rate in 2021-2022, AUD per 4 months	Rate in 2022-2023, AUD per 4 months
Residential property (single-family house)	19.76	20.78
Residential property with a discount (single-family house)	6.32	6.34
Residential property (flat/apartment)	6.32	6.64

Source: [23]

The billing system provides discounts for reduced runoff volumes. If residents of single-family dwellings reduce their runoff volume, they receive the same flat rate as residents of multi-family dwellings. Various methods can be used to achieve this goal, such as:

Installing large rainwater tanks that collect water from the roof and divert it for domestic use.

The use of infiltration systems such as rain gardens that trap stormwater and prevent it from entering the storm drainage system.

Use of permeable surfaces for pavements and pathways.

The "sponge city" concept has been successfully implemented in Wuhan and Beijing. This concept includes a surface runoff drainage system, associated green areas, and water bodies. In 2020, the system effectively coped with the increase in rainfall, reducing the number of flooded points from 162 to 30 compared to previous years, such as in 2016. Researchers at the University of Leeds estimated that the implementation of the sponge city concept in Wuhan saved around €510 million.

Improving and restoring the natural environment in cities contributes to CO_2 sequestration and improved adaptation to climate change. Urban natural solutions such as green roofs and water wetlands contribute to cooling cities, improving water quality and flood protection.

In the US, Seattle is implementing an Integrated Plan program to address combined sewer overflows and surface runoff pollution. The Capitol Hill Water Quality project is an example of a successful implementation of this program, incorporating biofiltration facilities to treat stormwater flowing into Lake Union. The project takes into account the topography of the city: water passes through a diversion basin, is treated in drainage ditches, and passes through grassy areas to filter out impurities.

5 Assessing the Cost-Effectiveness of an Integrated Approach to Surface Water Management through Ecosystem Solutions

According to the Millennium Ecosystem Assessment (MA) programme announced back in 2000 by UN Secretary-General Kofi Annan, ecosystem services can be categorized into 4 types, [24]:

– provisioning services;
– regulating services;
– cultural services;
– supporting services.

Supporting ecosystem services stand out from other types of ecosystem services - provisioning, regulating, and cultural - because their impacts on people are indirect and can persist over long periods of time. For example, the process of soil formation can take many decades or even centuries. The other types of ecosystem services depend on supporting services because they are usually interconnected and have different physical, chemical, and biological underpinnings, [25].

Supporting services relate to certain biophysical structures or processes of ecosystems such as soil, trees, and other plants that play a key role in maintaining water balance. These services are also the basis for the provision of other services directly important to people, such as improving water quality, cleaning the air, securing wood supplies, and providing food from wildlife. The benefits of such ecosystem services can be seen, for example, in reduced flood risk, [25].

Let us consider the relationship between ecosystems, services, and benefits in Figure 10.

Organizations, cities, and infrastructure projects can also benefit from ecosystem services through the use of resources such as water or protection from natural disasters such as flooding. In certain cases, this may provide an opportunity to utilize more efficient alternative methods instead of more costly technical solutions, [26].

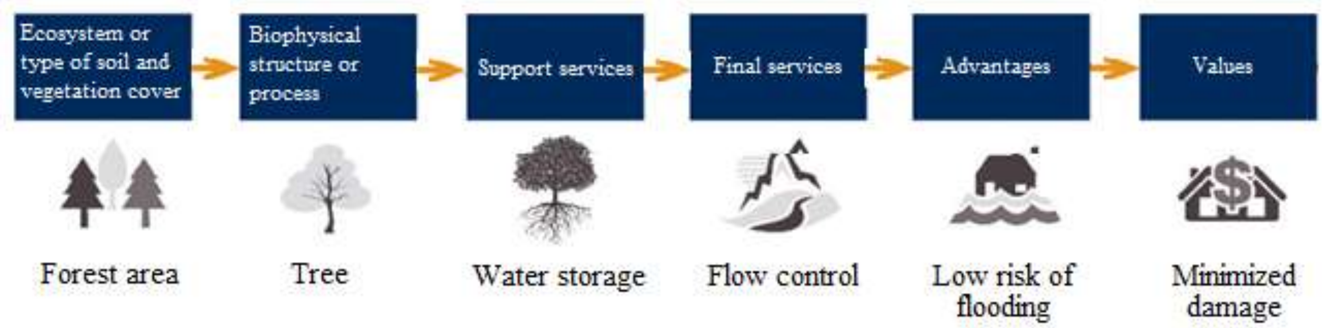

Fig.10: Relationship between ecosystems, services, and benefits

The ideas of natural solutions and the ecosystem approach are becoming increasingly common in national planning and regulatory documents, reflecting the general trend towards a green economy. This interest on the part of governments is driven by the recognition of the importance of conserving and sustainably managing natural resources in the context of combating climate change, as well as the recognition that national economies are highly dependent on natural resources. Estimates by the International Expert Council on Biodiversity and Ecosystem Services (IPCC) indicate that more than half of the world's GDP relies heavily on ecosystem services, in both developed and developing countries. Examples of support for natural solutions include initiatives in the Netherlands, such as the allocation of funds from the city budget for rain garden projects in Rotterdam in 2016, and the issuance of USD 5 billion green bonds by the Ministry of Finance in 2019 to finance riverine natural solutions projects.

A comparative study of two options for deploying infrastructure to manage stormwater runoff: the traditional (grey) scenario and the ecological (green) scenario based on the use of ecosystem services. The traditional scenario involves the installation of engineering systems to drain rainwater and the construction of treatment plants, after which the treated water is discharged into the river. The ecological scenario of "city in a garden" includes rainwater runoff management using nature-like technologies and green infrastructure such as bio-drainage ditches, rainwater harvesting in tanks for domestic needs, and the creation of an artificial reservoir in the city, [27].

The economic comparison of stormwater management options is presented in Table 3.

Table 3. Economic comparison of stormwater management options

Technical Solution	Traditional approach	City in the Garden project	difference, %
Pond construction		119,700,000	
Rain gardens		247,740,000	
Bio-drainage ditches		325,000,000	
Construction of local sewage treatment plants	1,250,000,000		
Construction of storm drainage	390,000,0000		
Total capital expenditures, KZT	1,640,000,000	692,443,000	-57%
Repair and maintenance costs, KZT, per year	54,666,665	34,622,150	-36.7%

The analysis of the data from Table 3 allows us to draw the following conclusions:

The application of green infrastructure to manage rainwater runoff in low-density cities significantly reduces both capital and operating costs compared to the traditional approach (by a factor of 1.6-2.4), [28].

In the garden city scenario, greenhouse gas emissions were 1.5% lower than in the traditional scenario. With an increase in the carbon price, which is typical for the world practice and can be implemented in Russia as well, the difference in costs can be significant. In addition, cooling costs in the garden city project were 27% lower compared to the traditional project.

The expansion of green spaces optimizes the load on urban infrastructure and improves the quality of life for city dwellers, with the type of plants planted playing an important role. Trees help improve air quality and are more effective in reducing the island's heat island effect than grasses and shrubs.

However, not all of the benefits of using ecosystem services have been taken into account. For example, reduced maintenance and construction of sewers lead to reduced flood risk and associated costs, but this was not considered in this study.

Effective implementation of green infrastructure requires significant amounts of undeveloped land. Green infrastructure, including parks, forest plantations, and water bodies, plays an important role in improving the ecological situation, reducing air pollution, and improving water quality. In the context of urbanization, when natural areas are limited, the use of undeveloped land becomes key to creating large ecological zones. These areas allow the integration of natural elements into the urban environment, ensuring the coherence and effectiveness of green infrastructure. Careful design and long-term planning based on sustainable development principles are necessary to preserve biodiversity and adapt to changing conditions. Green infrastructure also improves quality of life, promotes tourism, and creates comfortable conditions for residents. With a shortage of undeveloped land in existing cities, using undeveloped land helps avoid the demolition of buildings and reduces the cost of implementing projects, making them more cost-effective and sustainable in the long term.

It is important to note that utilizing green infrastructure requires careful design and the availability of significant amounts of undeveloped land. For example, the "city in a garden" project requires the allocation of over 300 hectares of additional land, the market price of which in Kazan is approximately RUB 7.6 billion, [29].

Thus, the "garden city" project demonstrates good economic performance (not taking into account the cost of land). However, the high price of land in large cities creates difficulties in justifying such projects in terms of economic feasibility. The inclusion of the "willingness to pay" methodology in economic evaluations of "green" projects in Kazakhstan is not always adequate, as the majority of the population shows a low willingness to pay for such services.

Nevertheless, the global experience of research on the impact of environmental factors on property prices shows that the creation of green areas can significantly increase the value of land and property in these areas. This is confirmed by various valuation methods, such as geodynamic pricing for the cities mentioned above. In this way, developers are compensated for alienating additional land for green infrastructure through higher property prices and the willingness of future residents to pay for this increase.

6 Conclusion

In the context of urbanization and high land costs, the implementation of green infrastructure faces serious economic barriers. Although the initial costs may be high, ignoring the long-term benefits such as improved air quality, lower temperatures, and higher living standards may be a strategic mistake. Integrating green infrastructure management into urban planning and revising urban development regulations can contribute to more sustainable urban development. These findings are relevant not only for Kazakhstan but also for other countries where urbanization is creating similar problems. Countries with highly developed economies and rapidly growing cities, such as the US, EU countries, and China, also face difficulties in implementing green infrastructure due to economic and planning barriers. Current research confirms that investments in such projects can significantly improve urban ecology and reduce the load on utility systems, which emphasizes the importance of considering the long-term benefits of using green technologies. Future research should focus on assessing the cost-effectiveness of new technologies, developing models to predict the performance of wastewater treatment plants, creating rainwater collection and treatment systems, and exploring the potential for recycling treated water for technical purposes. This research direction will help to better understand the potential benefits and challenges of integrating green infrastructure into urban management and planning. This study provides a comprehensive overview of the challenges and solutions associated with the implementation of green infrastructure in Kazakhstan and other urbanized regions, focusing on specific issues such as deterioration of sewer systems and insufficient development of storm sewers. It offers specific recommendations for improving urban ecology and infrastructure, contributing to the development of more sustainable solutions and creating a basis for further research and practical actions in the field of sustainable urban environment development.

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In preparing this work, the authors utilized ChatGPT to:
-refine wording and improve clarity of presentation;
-review and enhance the logical structure of the content.
After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Conflict of Interest

The authors have no conflicts of interest to declare.