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INVESTIGATION OF THE EFFECTS OF POPULATION GROWTH AND URBANIZATION ON WATER CONSUMPTION IN KAZAKHSTAN USING MATHEMATICAL MODELING METHOD

Annotation. As is the case worldwide, population growth and urbanization are increasingly progressing processes in Kazakhstan. Therefore, it is anticipated that the increasing water demand driven by urbanization will exert pressure on water resources. Identifying this pressure and its potential effects systematically and taking necessary measures are of critical importance. In this context, this study examines the impact of population and urbanization growth on water consumption in Kazakhstan using data from the Kazakhstan National Statistics Bureau and mathematical modeling methods. The findings indicate that Kazakhstan's population, which stands at 20 million in 2024, is projected to reach 24 million by 2040 and 27 million by 2050. Furthermore, 70.7% of this population is expected to reside in urban areas, while the rural population is anticipated to decrease by 27.5%. In the study, population growth in large cities was analyzed. The urbanization rate between 2019 and 2024 stands out. In the future, it is possible that water resources will become insufficient and fail to meet the demand for water. With urbanization, the increasing demand for water brings to the fore the necessity of efficient use and protection of water resources. Within the scope of the study, the effects of the increasing urbanization rate on per capita daily water consumption have been projected, potential problems related to water resources have been identified. The per capita water demand has been rapidly increasing annually due to population growth. Future water demand forecasts have also been made to assess the impact of urban population growth on per capita daily water consumption. Therefore, this study emphasizes the importance of implementing critical measures to ensure the efficient management of water resources.

Keywords: Kazakhstan; mathematical modelling; urbanization; water consumption.

Introduction

Urbanization is a significant phenomenon that affects social and economic systems as well as environmental balance on a global scale. Particularly over the past two decades, the increasing population and the resulting rise in water demand have brought the issue of a global water crisis to the forefront.

With the advancement of industry, the industrialization of agriculture and the strengthening of Industry 4.0 trends, the global tendency of migration from rural areas to urban centers has increased, accelerating urbanization rates worldwide [1].

Urbanization is defined as the process of increasing the role of cities in the development of society. In socio-economic, demographic, political, ethno-cultural and geographical dimensions, this process reflects the regional formation of society, its productive capacity and patterns of settlement.

Kazakhstan, one of the largest countries in Central Asia, has experienced rapid urbanization and economic growth since gaining independence following the dissolution of the

Soviet Union. The disparity between urban and rural populations in Kazakhstan has become more pronounced. The rate of population growth and urbanization has significant impacts on the country's water resources, as well as its ecological and environmental structures. Therefore, the use and sustainable management of water resources are of critical importance for the country's future.

According to UN data, currently, 2 billion people worldwide lack access to clean and safe drinking water. Countries and regions that obtain 25% or more of their drinking water through desalination are at risk. The World Resources Institute predicts that by 2040, this problem will become even more widespread 44 countries may face "extremely high" or "high" levels of water stress, including Kazakhstan.

The identified causes of pressure on water systems are accelerating urbanization, population growth, climate change and economic development.

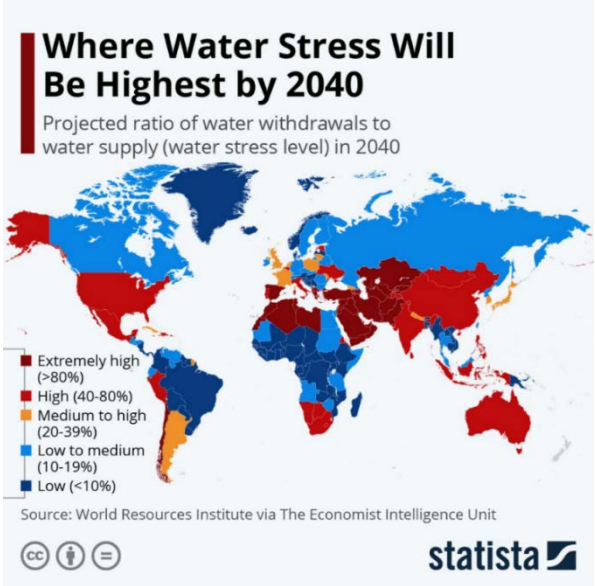

Figure 1 – Water Stress by Country: 2040

It is important to note that the main cause of the worsening global water crisis is urbanization.

Increasing Water Demand in Kazakhstan: The Effects of Urbanization

Recently, the population of the capital has been facing the growing issue of water scarcity. Several factors contribute to this problem. The most significant ones are the rapid increase in population and the acceleration of urbanization. For example, last year, there were water cuts in some neighborhoods of Astana. When the first master plan of the capital was prepared, it was estimated that the population would be between 800,000 and 900,000 by 2023. In 2010, the city administration predicted that the population of the capital would reach 1.2 million by 2030, 20 years later. However, this number was reached in 2020. As of now, the population of Astana is 1,430,117 according to official figures [2].

Kazakhstan may fall into the category of countries facing "high water scarcity" by 2050. In this regard, the President of Kazakhstan, Kassym-Jomart Tokayev, made statements during a council meeting on the country's socio-economic development. Currently, more than 600,000 people in the country are facing the issue of access to clean drinking water. The Ministry of Water Resources and Irrigation was established in Kazakhstan on September 1, 2023, to develop policies related to the conservation and management of water resources, as well as

water scarcity. Some experts predict that between 2030 and 2050, the price of water will exceed that of gold and oil.

This study was conducted with the aim of examining the impacts of population growth and urbanization on water consumption through mathematical modeling methods and identifying measures to prevent potential future problems. In this context, the growth of urban and rural populations in Kazakhstan was calculated and compared using different methods. Accordingly, the rates of increase in the urban population and decrease in the rural population were determined, and projections for the future were made. Based on population growth, future water demands were estimated. In parallel, considering that the country's water resources may become insufficient to meet the increasing demand, preventive measures that can be taken from now on were identified to address this critical issue.

Urbanization Process in Kazakhstan

Kazakhstan is undergoing an active urbanization process, characterized by the rapid growth of the urban population and the expansion of urban infrastructure and industry. The migration from rural to urban areas is driven by various social and economic factors. The increase in the urban population in Kazakhstan has occurred due to two main factors: first, migration from rural areas and from small, economically depressed cities that lost their economic profile and commercial vitality during the restructuring years and second, natural population growth.

According to data from the National Bureau of Statistics of Kazakhstan, as of early 2024, the urban population reached 12.5 million people, accounting for 62% of the country’s total population, while 7.6 million people (37.8%) reside in rural areas.

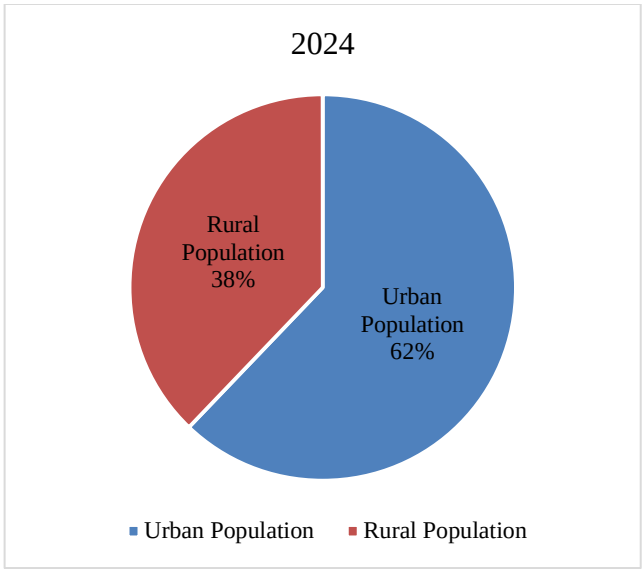

Figure 2 – Urban and Rural Population Distribution in Kazakhstan [3]

According to the *World Urbanization Prospects*, more than 40% of the urban population lives in metropolitan areas with populations exceeding one million. Of this urban population, 22% live in cities with 1–5 million inhabitants and 41% reside in cities with populations below 300,000. In Kazakhstan, 38% and 41% of the urban population live in such cities, respectively [4].

The graph in Figure 3 was created using demographic data from the National Bureau of Statistics of Kazakhstan. It visualizes the total population, as well as the distribution of urban and rural populations, between the years 2010 and 2024. In this graph, Kazakhstan’s total

population is represented by the green line, the urban population by the blue line and the rural population by the yellow line. A clear distinction between the urban and rural population trends can be observed.

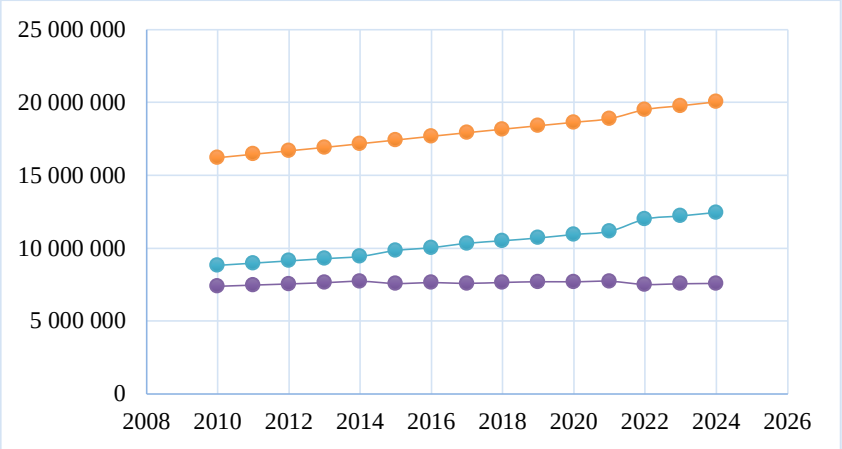

Figure 3 – Population of Kazakhstan (2010-2024)

According to the data from the Bureau of National Statistics of the Republic of Kazakhstan, there are 89 cities and 6256 villages in Kazakhstan. Cities in Kazakhstan are classified into three categories: republican, regional and district status. This classification is based on the administrative, economic and social significance of the cities. It allows for the implementation of governance policies that are appropriate to the specific characteristics of each category. Among the 89 cities in Kazakhstan, 3 have republican status, 38 are designated as regional centers and 47 have district center status. The cities of Astana, Almaty and Shymkent each with a population exceeding one million stand out as the country's leading centers of science, education, culture and are among the fastest growing urban areas.

Water resources and use in Kazakhstan

Although Kazakhstan has a vast land area, it possesses limited water resources and exhibits significant regional imbalances in water availability. A large portion of its water resources depends on inflows from neighboring countries, highlighting the country's reliance on transboundary rivers.

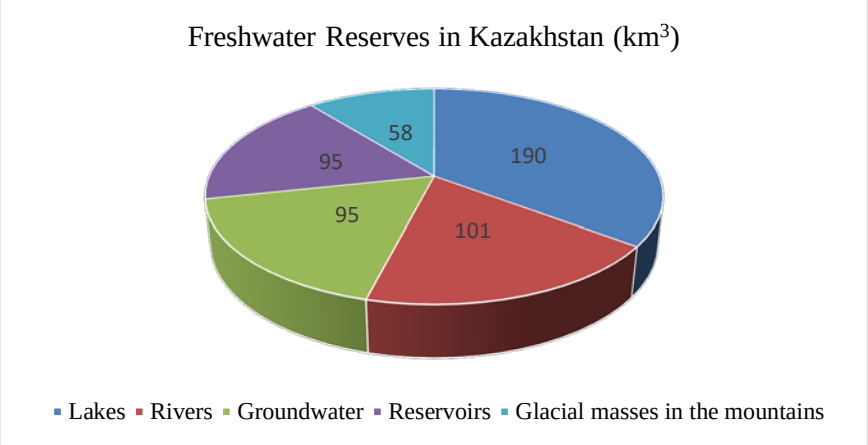

Figure 4 – Freshwater Reserves in Kazakhstan

According to data, the total volume of freshwater reserves in Kazakhstan is estimated at 539 km³ [5]. Water resources entering Kazakhstan from neighboring countries are primarily delivered via rivers. For instance, Kazakhstan receives approximately 8 km³ of water annually from Russia, 19 km³ from China, 15 km³ from Uzbekistan, 3 km³ from Kyrgyzstan through transboundary rivers. In total, of the 101 km³ of river water available, 45 km³ originates outside the country, while 56 km³ is generated within Kazakhstan's borders.

The main volume of water resources in Kazakhstan is provided by surface waters, with an average annual volume of 101 km³. Of this, 56% is formed locally, while the remaining 44% comes from the inflow of transboundary rivers from China, Uzbekistan, Russia and Kyrgyzstan. According to the hydrographic principle, eight river basin management regions have been identified in the territory of the Republic: the Aral-Syrdarya, Balkhash-Alakol, Yertis, Yesil, Zhaiyk-Caspian, Nura-Sarysu, Tobil-Torgay and Shu-Talas basins [6].

Table 1 – Water consumption by sector in Kazakhstan **(m³) [7]**

	2019	2020	2021	2022	2023
Total	20 955	20 307	19 999	20 443	20 480
Water supply for agriculture	13 178	12 361	11 742	11 546	11 329,5
Industrial needs	5 600	5 685	5 753	5 806	5 908,4
Domestic and drinking water needs	792	800	868	1125,6	908,3

Water scarcity in Kazakhstan is becoming an increasingly critical issue with each passing year. Alongside urbanization, the growing demand for water highlights the urgent need for the efficient use and protection of water resources. Moreover, with the rise in population and industrialization, water consumption particularly in sectors such as agriculture and industry is gaining even greater significance. In this context, the effective management of water resources has become a crucial matter for ensuring a sustainable future.

Materials and methods of research

In this study, statistical data were collected to investigate the increase in urbanization in Kazakhstan and the corresponding rise in water demand.

The data of the National Bureau of Statistics of Kazakhstan on "Demography", "Ecological Indicators of Environmental Monitoring and Assessment, Water Resources", annual values of water consumption per capita were used. Academic studies and scientific articles examining the urbanization process in Kazakhstan, the status of the country's water resources and related water issues have been utilized in this research.

Datasets

In this study, data on Kazakhstan's total population, urban and rural population distribution, urbanization rate, water consumption were collected. The population data for the period between 2010 and 2024 served as the basis of the analysis. The data were categorized into total population, urban and rural population.

Data Analysis Methods: Application of the Linear Growth Model

The mathematical modeling of urban growth in Kazakhstan is a highly effective method for understanding, analyzing, forecasting urbanization processes and dynamics. In this study, population dynamics including total, urban and rural population figures in Kazakhstan between 2010 and 2024 were analyzed to make future projections using a mathematical model. The linear growth model is used to estimate future population based on historical data. The general equation of the linear growth model is defined as follows:

$$X_2 = X_1 + K \times (t_2 - t_1)$$

X_2 = Total / Urban / Rural population in the projected year
X_1 = Population value at the beginning of the model (year 2024)
K = Population growth rate
t_1, t_2 = Time values

Table 2 – Population of Kazakhstan (2010-2024) [3]

Time (t)	Total Population	Urban Population	Rural Population
2010	**16 203 274**	**8 819 620**	**7 383 654**
2011	16 440 470	8 973 922	7 466 548
2012	16 673 933	9 127 543	7 546 390
2013	16 910 246	9 277 871	7 632 375
2014	17 160 855	9 433 575	7 727 280
2015	17 415 715	9 837 025	7 578 690
2016	17 669 896	10 035 577	7 634 319
2017	17 918 214	10 331 492	7 586 722
2018	18 157 337	10 509 796	7 647 541
2019	18 395 567	10 698 208	7 697 359
2020	18 631 779	10 938 652	7 693 127
2021	18 879 552	11 151 376	7 728 176
2022	19 503 159	11 991 238	7 511 921
2023	19 766 807	12 209 896	7 556 911
2024	**20 033 842**	**12 451 192**	**7 582 650**

Research results

Population Projection for Kazakhstan

To determine the population growth rate, the average value of *K* was calculated.

$$\mathbf{K} = \frac{20\,033\,842 - 16\,203\,274}{2024 - 2010} = \mathbf{273\,612}$$

X_1 (2024) = 20 033 842

X_2 (2030) = 20 033 842 + 273 612 × (2030-2024) = 21 675 514

The total population projected for every five-year interval between 2030 and 2100 was evaluated using an Excel table. The linear growth model equation was entered into Excel as a formula and population values (X2) were calculated for every five years.

Kazakhstan's projected total population for future years has been visualized through a graphical representation.

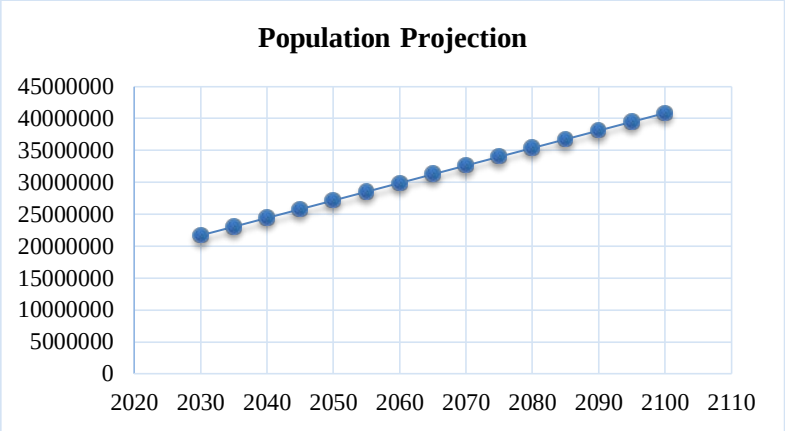

Figure 5 – Population Projection for Kazakhstan (2030–2100)

Urban Population Projection

First, the average growth rate (*K*) for the urban population is calculated.

$$\mathbf{K} = \frac{12\,451\,192 - 8\,819\,620}{14} = \mathbf{259\,398}$$

X_1 (2024) = 12 451 192

X_2 (2030) = 12 451 192 + **259 398 × (2030-2024)** = 14 007 580

The projected urban population for every five-year interval between 2030 and 2100 was evaluated using an Excel table. The linear growth model equation was entered into Excel as a formula and the urban population values (X_2) for each five year interval were calculated accordingly.

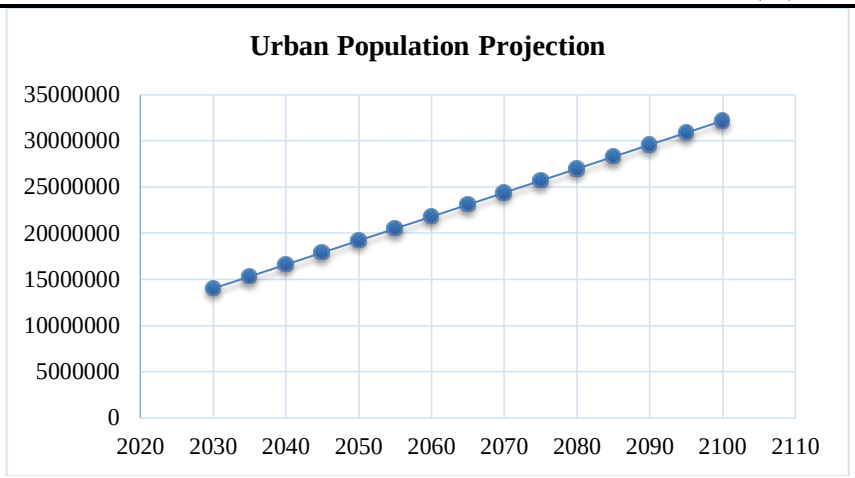

Figure 6 – Projection of Kazakhstan's Urban Population

A graph has been created for the projected urban population. It has been observed that the urban population is expected to increase.

Rural Population Projection

The annual growth rate (*K*) for rural areas was calculated and the decreasing population trend has been taken into account.

$$\mathbf{K} = \frac{7\,582\,650 - 7\,632\,375}{2024 - 2013} = -4520{,}45$$

X_1 (2024) = 7 582 650

X_2 (2030) = 7 582 650 **+ (- 4520,45) × 6 = 7 555 527**

The projected rural population for every five year interval between 2030 and 2100 was evaluated using an Excel table. The linear growth model equation was entered into Excel as a formula, the rural population values (X_2) for each five year interval were calculated. It has been observed that the rural population is expected to decline.

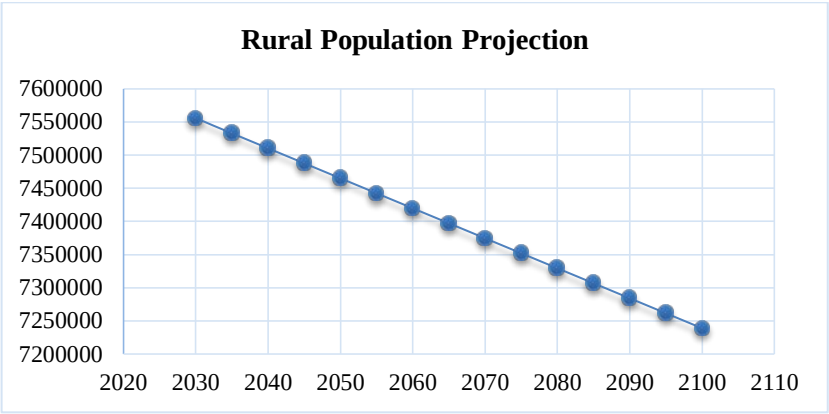

Figure 7 – Projection of Kazakhstan's Rural Population

Water Consumption Calculation

One of the objectives of this study is to estimate population growth and the corresponding changes in water consumption. In Kazakhstan, per capita water consumption is approximately 150–200 liters per day in urban areas and 50–100 liters in rural areas [8].

Within the scope of this study, the urban population growth rate was projected using the linear growth model and a water consumption forecast was conducted to assess the impact of this increase on daily per capita water demand. The results obtained will assist in predicting future water demand and in developing necessary recommendations for water resource management.

To analyze the relationship between water consumption and urbanization, a basic water consumption calculation formula can be applied.

W (daily water consumption) = P × C

P – Population

C – Per capita daily water consumption (liters/day)

Based on the projected urban population data for the years 2030–2100 obtained using the linear model, water consumption estimates were calculated in Excel. In the calculation, the daily per capita water consumption was considered as *C = 200 L/day.*

Table 3 – Future Water Consumption Forecast (Urban Population)

Time (t)	**Population (P)**	**W**		
		Water Consumption **(L)**	Water Consumption **(m^3)**	Water Consumption **(thousand tons)**
2030	14 007 580	2801516000	2801516	2801,52
2035	15 304 570	3060914000	3060914	3060,91
2040	16 601 560	3320312000	3320312	3320,31
2045	17 898 550	3579710000	3579710	3579,71
2050	19 195 540	3839108000	3839108	3839,11
2055	20 492 530	4098506000	4098506	4098,51
2060	21 789 520	4357904000	4357904	4357,9
2065	23 086 510	4617302000	4617302	4617,3
2070	24 383 500	4876700000	4876700	4876,7
2075	25 680 490	5136098000	5136098	5136,1
2080	26 977 480	5395496000	5395496	5395,5
2085	28 274 470	5654894000	5654894	5654,89

2090	29 571 460	5914292000	5914292	5914,29
2095	30 868 450	6173690000	6173690	6173,69
2100	32 165 440	6433088000	6433088	6433,09

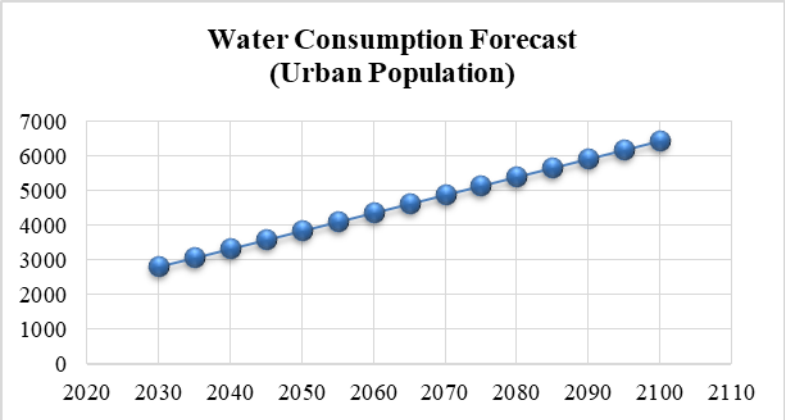

Figure 8 – Water Consumption Forecast

In Table 3 and the graph in Figure 8, the changes in daily per capita water consumption over the years are presented. It is observed that with the progression of urbanization, daily per capita water consumption will increase, indicating how water demand is expected to evolve. This situation emphasizes the importance of sustainable management of water resources.

The model results present the projected total, urban, rural populations for every five-year interval between 2030 and 2100. It has been observed that the urban population is increasing, while the rural population is declining. The linear model has been applied separately for each population category. The growth in the total population is largely attributed to the increase in urban areas.

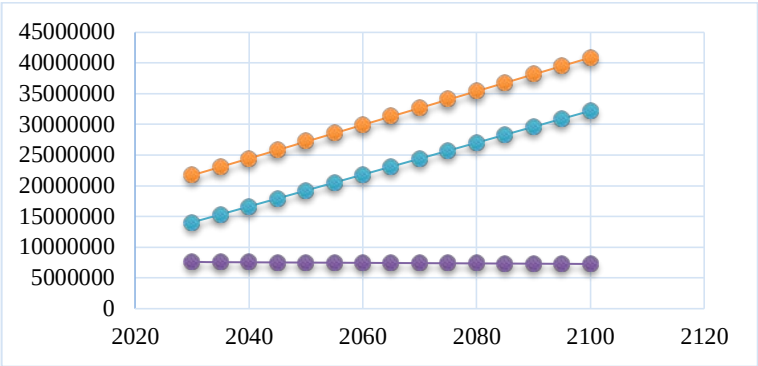

Figure 9 – Projected Total, Urban and Rural Population in Kazakhstan

Urban and Rural Population Change: 2014-2024

Based on the data from the Kazakhstan National Statistics Bureau, the changes in urban and rural populations have been analyzed. In the last 10 years, the share of the urban population has increased from 55% to 62.1%, while the rural population has decreased from 45% to 37.8%.

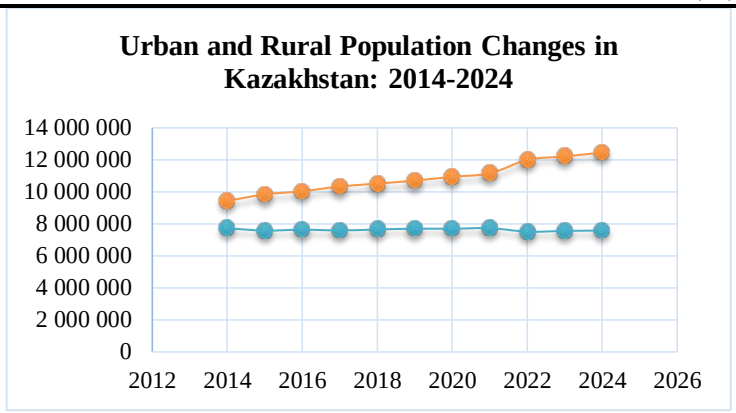

Figure 10 – Urban and Rural Population Changes in Kazakhstan: 2014-2024

It has been determined that the Urban Population given by the green line has increased in the last ten years. It is shown that the Rural Population rate, represented by the blue line, has decreased over the past ten years.

Population Growth in Largest Cities

Five years ago (in 2019), the population of Astana, Almaty and Shymkent cities with republic status accounted for 21% of Kazakhstan's total population. By 2024, this proportion had increased to 24.4%. A consistent annual increase in the population of these major cities has been observed.

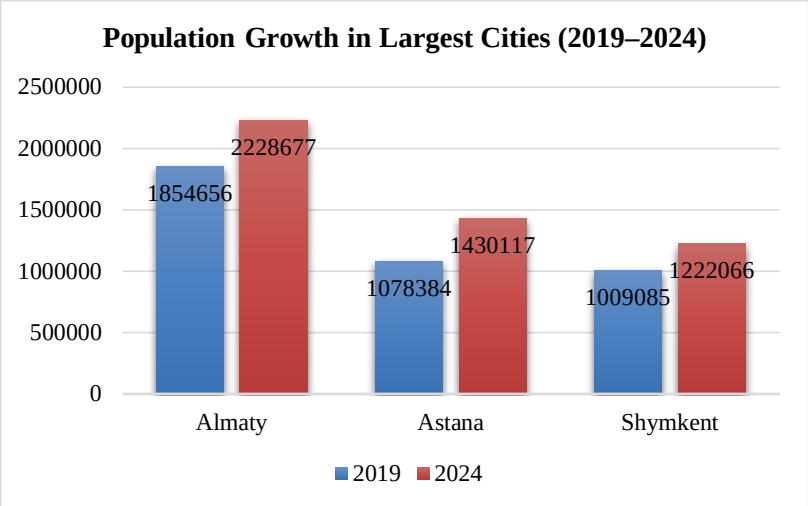

Figure 11 – Population Growth in Almaty, Astana and Shymkent [3]

The economic development of Almaty has led to a rapid increase in both the population and the urban area; since 2014, the urban area has more than doubled. In the last 20 years, the population of Almaty has doubled, reaching 2.2 million people.

In the last 12 years, the population of the Astana has also doubled. If the population of Astana increases to 2 million, the risk of drinking water scarcity will become quite serious.

Conclusion and Recommendations

In this study, data on the total population, urban and rural populations of Kazakhstan from 2010 to 2024, obtained from the Bureau of National Statistics of Kazakhstan, were analyzed. The increase in urbanization and its effects on water consumption were evaluated using a mathematical model. The dataset used in the study is based on Kazakhstan's annual population figures, urbanization rates and daily water consumption volumes. When the data

from 2010 to 2024 were analyzed, it was found that the average annual increase in the urban population was 259,398. This increase becomes more evident as the rural population declines. Within the scope of the study, the effects of the rising urbanization rate on per capita daily water consumption were projected and potential issues regarding water resources were identified. The per capita water demand has been rapidly increasing year by year in parallel with population growth. To assess the impact of urban population growth on per capita daily water consumption, future water demand was also estimated.

The rainwater management system implemented in Oslo, Norway, serves as a remarkable example of the efficient use of water resources. Collecting rainwater in special reservoirs, treating it and subsequently using it for irrigating green areas not only contributes to water conservation but also offers significant ecological benefits. Implementing similar approaches in Kazakhstan could provide effective solutions for the preservation of water resources. In this context, it is recommended that rainwater harvesting and treatment systems be initially tested through pilot projects in major cities of Kazakhstan.

In a period where the rate of urbanization is increasing and the demand for water is steadily growing, establishing branches of the world's leading universities in the field of water management and training qualified professionals is of great importance. Kazakhstan has taken a significant step in the field of education by deciding to open branches of 23 of the world's top universities.

The model used in the study provided a simple but effective method for estimating the total, urban and rural population growth of Kazakhstan. However, for further analysis, it is recommended to use different mathematical models.

Water resources have strategic importance in the economic, industrial and social development of a country. Population growth is one of the factors that affect water demand. The impact of other factors, such as climate change, on water resources should also be investigated. To ensure the effective and efficient use of water, innovative technologies must be applied in water management. The preparation of necessary plans and programs to ensure the optimal use of water resources is becoming increasingly important. The rapid growth of the urban population creates various risks in water consumption. Therefore, it is essential to develop sustainable urbanization policies and establish strategies that balance environmental, economic and social factors.

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ҚАЗАҚСТАНДАҒЫ ХАЛЫҚ САНЫНЫҢ АРТУЫ МЕН УРБАНИЗАЦИЯНЫҢ СУ ТҰТЫНУҒА ӘСЕРІН МАТЕМАТИКАЛЫҚ МОДЕЛЬДЕУ ӘДІСІ АРҚЫЛЫ ЗЕРТТЕУ

Аңдатпа. Әлем елдеріндегі секілді Қазақстанда да халық санының өсуімен бірге урбанизация процесі қарқынды түрде дамып келеді. Сондықтан, урбанизацияға байланысты артып келе жатқан суға деген сұраныс су ресурстарына қысым түсіреді деп күтілуде. Бұл қысымды және оның ықтимал салдарын жүйелі түрде анықтау және қажетті шараларды қабылдау аса маңызды. Осыған орай, бұл зерттеуде Қазақстан Республикасы Ұлттық статистика бюросының деректері және математикалық модельдеу әдістері пайдаланыла отырып, Қазақстандағы урбанизация мен халық санының артуының су тұтынуына әсері талданды. Зерттеу нәтижелері бойынша, 2024 жылы 20 миллионға жеткен Қазақстан халқының саны 2040 жылға қарай 24 миллионға, ал 2050 жылға қарай 27 миллионға жетеді деп болжануда. Бұл халықтың 70,7%-ы қалаларда өмір сүретінін, ал ауыл халқының 27,5%-ға азаятынын көрсетеді. Зерттеу барысында ірі қалалардағы халық санының өсуі де қарастырылды. Әсіресе 2019–2024 жылдар аралығындағы урбанизация қарқыны – ерекше назар аударарлық жайт. Болашақта су ресурстарының жеткіліксіз болып, суға деген сұранысты қанағаттандыра алмау қаупі бар. Урбанизациямен қатар артатын суға деген сұраныс, су ресурстарын тиімді пайдалану мен қорғаудың маңыздылығын алдыңғы орынға шығарады. Зерттеу аясында урбанизация деңгейінің артуының адамның тәуліктік су тұтыну мөлшеріне ықпалы болжанып, су ресурстарының тапшылығына әкелуі мүмкін ықтимал мәселелер анықталды. Халық санының артуына байланысты адам басына шаққандағы су сұранысы жыл сайын жылдам қарқынмен өсіп келеді. Сонымен қатар, қала халқы санының өсуінің тәуліктік су тұтыну көлеміне әсерін бағалау үшін болашақтағы суға деген сұраныс болжамдары жасалды. Сондықтан бұл зерттеу су ресурстарын тиімді басқаруды қамтамасыз ету үшін маңызды шараларды жүзеге асыру қажеттігін атап көрсетеді.

Кілт сөздер: Қазақстан; математикалық модельдеу; урбанизация; су тұтыну.

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ИССЛЕДОВАНИЕ ВЛИЯНИЯ РОСТА ЧИСЛЕННОСТИ НАСЕЛЕНИЯ И УРБАНИЗАЦИИ В КАЗАХСТАНЕ НА ВОДОПОТРЕБЛЕНИЕ С ИСПОЛЬЗОВАНИЕМ МЕТОДА МАТЕМАТИЧЕСКОГО МОДЕЛИРОВАНИЯ

Аннотация. Как и в других странах мира, в Казахстане процесс урбанизации активно развивается вместе с ростом численности населения. В связи с этим ожидается, что растущий спрос на воду, вызванный урбанизацией, окажет давление на водные ресурсы. Систематическое определение этого давления и его возможных последствий, а также принятие необходимых мер имеет важное значение. В данном исследовании, на основе данных Бюро национальной статистики Республики Казахстан и методов математического моделирования, проанализировано влияние урбанизации и роста численности населения на водопотребление в стране. Согласно результатам

исследования, численность населения Казахстана, достигшая 20 миллионов в 2024 году, к 2040 году может увеличиться до 24 миллионов, а к 2050 году до 27 миллионов. Это показывает, что 70,7% населения будет проживать в городах, а сельское население сократится на 27,5%. В исследовании также рассмотрен рост численности населения в крупных городах, особенно стоит отметить темпы урбанизации в период с 2019 по 2024 годы. В будущем существует риск того, что водных ресурсов окажется недостаточно для удовлетворения спроса на воду. Рост спроса на воду в условиях урбанизации выдвигает на первый план важность эффективного использования и охраны водных ресурсов. В рамках исследования был спрогнозирован рост суточного водопотребления на человека в связи с увеличением уровня урбанизации, а также выявлены возможные проблемы, которые могут привести к дефициту водных ресурсов. В связи с ростом численности населения ежегодно быстро увеличивается спрос на воду в расчёте на душу населения. Кроме того, для оценки влияния роста численности городского населения на объёмы суточного водопотребления были сделаны прогнозы будущего спроса на воду. Таким образом, данное исследование подчёркивает необходимость реализации важных мер для обеспечения эффективного управления водными ресурсами.

Ключевые слова: Казахстан; математическое моделирование; урбанизация; водопотребление.