Use of water resources in the northern territories of Yakutia for industrial development: a forecast model

Angelina Egorova[1,2*] and *Elena* Grigoryeva[2]

[1]Lomonosov Moscow State University, Kolmogorova Street 1c46, Moscow 119234, Russia
[2]Institute of Regional Economics of the North, North-Eastern Federal University, 677000 Yakutsk, Oyunskogo Street 27, Russia

Abstract. Active industrial development and the implementation of large-scale mining projects in Russia's northern and Arctic territories directly impact the use and pollution of water resources. This also places significant pressure on aquatic ecosystems, posing a risk to biodiversity and the state of aquatic biological resources. Monitoring environmental indicators is particularly important in high-risk areas – northern mining-intensive territories. The objective of this study is to predictively assess the impact of industrial development on water resources in northern territories using mathematical and statistical models across municipal districts, using the Republic of Sakha (Yakutia) in the Russian Federation as an example. The study utilizes a combination of economic and mathematical methods, including time series dynamics, the sum of ranks method, rating analysis, multilevel modeling, decoupling, and others. The combination of cluster and multilevel modeling enabled a comprehensive analysis of the problem under consideration. Based on the constructed models, a predictive assessment of water withdrawal volume dynamics in the republic's TOP-5 producing districts was provided. The practical significance of the obtained results lies in the development of computational algorithms for multi-level modeling and forecasting of water consumption and environmental and economic impacts on water resources in districts and the republic as a whole, as well as for planning sustainable nature management and conservation of Arctic biodiversity

1 Water resources of the northern territories

The category of northern territories in Russia is characterized by economic underdevelopment due to key factors: extreme climate, inaccessibility, fragile arctic and subarctic natural systems, economic underdevelopment, etc. The ecosystem resilience of northern territories is generally unstable. Water in the North is the basis of life and a key natural resource for indigenous peoples. Northern ecosystems are characterized by low self-purification capacity, as cold water and low biodiversity slow the self-purification process.

* Corresponding author: snp077@yandex.ru

External human impacts on the ecosystem sometimes cause irreversible damage or reduce the self-purification capacity.

Industrial development and mineral extraction have a significant negative external impact on the ecosystem of northern territories, as confirmed by a number of scientific studies [1, 2, 3]. Therefore, we believe that predictive modeling of water resource use in Russia's northern territories is highly correlated with the pace of industrial development and its prospects. Furthermore, monitoring water resource use should consider all types of water use: traditional (fishing, reindeer herding, domestic), industrial (at industrial facilities), and transport (shipping, Northern delivery).

Monitoring and assessing water resource use in northern territories requires a comprehensive systems approach. Research methodology must consider key factors in the unique natural, climatic, and socioeconomic conditions of these regions. The intensity of impact and pollution of water resources in local areas is largely determined by the characteristics of regional and sectoral economies. However, the key challenge in monitoring and forecasting natural resource use in northern territories is the lack of data (observations) and the high cost of any fieldwork [1,4]. Therefore, to develop a methodological toolkit, available economic metrics from municipal districts in the region were used, employing an integrated and adaptive approach using modern econometric methods. Since northern territories often occupy vast areas with asymmetric infrastructure, an approach to distributing local territories by specialized industries at the level of the region's municipal districts was used to obtain an adequate forecast estimate. The proposed methodological approach to model-based forecasting of water resource use was tested using the example of Russia's largest northern region - the Republic of Sakha (Yakutia) and its municipal districts.

The methodological basis for research in the field of water resources management was work in the field of: anthropogenic impact on the environment [5,6], development of water use strategies [4,7], development of tools to support management decision-making [8, 9], etc.

The operating principles of natural resource subsystems, including regional water management systems, their organizational characteristics, and operational mechanisms have been extensively studied in the scientific literature. Numerous studies confirm their key role in shaping the preconditions for the development of regional and national economic systems. Various strategic management tools for their development, including water consumption, have also been proposed. However, the problem of comprehensively assessing the multidimensional impacts on water resources and related economic processes remains understudied.

Particularly noteworthy is the limited effectiveness of regional water resource management strategies. Key problematic aspects include a lack of proper integration with sectoral and territorial development strategies, as well as insufficient consideration of intersectoral aspects of water consumption across various economic sectors. Therefore, the development of integrated water resource management models, including a system for monitoring and forecasting local water consumption, with escalation to the upper level, is urgent. This issue requires an interdisciplinary approach combining economic, environmental, and natural resource management methods to develop effective mechanisms for sustainable water use. The obtained results have practical implications for decision-making in water consumption management in northern territories, particularly in the context of industrial development.

1.1 Industrial development of the districts of Yakutia

1.1.1 Spatial analysis of the location of industrial facilities

The Republic of Sakha (Yakutia) plays a strategic role in Russia's mining sector, being the country's primary supplier of diamonds, gold, tin, and antimony. Consequently, numerous mining operations in some areas have a significant impact on water resources and the environment. Yakutia's main mining districts with the greatest economic value are located in the west and south of the republic, as shown in Figure 1.

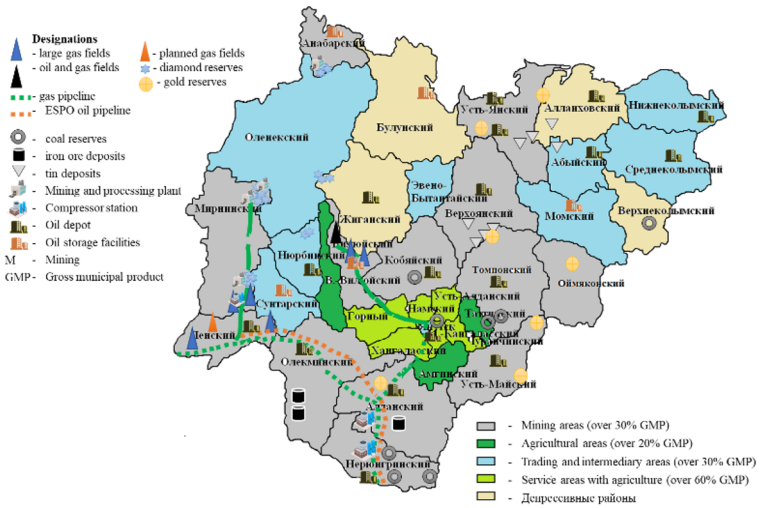

Fig. 1. The impact of mining on the economy of the districts of the Republic of Sakha (Yakutia).

The Western Economic Zone is a dynamically developing region with a concentration of strategically important diamond, gold, oil, and gas deposits. Active hydrocarbon resource development is accompanied by the development of pipeline infrastructure (ESPO, Power of Siberia) directed to China. The Southern Economic Zone is a traditional industrial region with a century-long history of gold mining (Aldansky District) and more than half a century of coal mining (Neryungri District). The republic's capital, Yakutsk, serves as a transportation and economic hub, a logistics hub, a center for manufacturing, and a hub for the service economy. Meanwhile, coal mining continues in the suburban town of Kangalassy to meet the local needs of the city and surrounding areas.

The municipal districts of Yakutia were grouped using cluster analysis based on the volume of shipped domestically produced goods by type of activity, which together contribute to the district's gross municipal product. Five groups were identified (Figure 1):

- 1. Mining districts (n=13), where the share of mineral extraction activity exceeds 30% of the district's GMP.
- 2. Agricultural districts (n=3), where the share of agricultural activity exceeds 20% of the district's GMP.
- 3. Service districts of the agglomeration with agriculture (n=7), where the share of agricultural activity and retail turnover exceeds 60% of the district's GMP.
- 4. Trade and intermediary districts (n=8), where the share of retail turnover exceeds 30% of the district's GMP.

- 5. Depressed districts (n=4), where there is no dominant industry specialization and the dynamics of the district's GMP are below the national average.

The results of the factorial Analysis of Variance (ANOVA) confirm the significance of differences between the groups and their increasing differentiation.

1.1.2 Branches of specialization of the republic and their prospects

The share of the mining industry in the gross regional product of the Republic of Sakha (Yakutia) increased from 46% to 64% over the analyzed period of 2006-2023. An analysis of the republic's sectoral structure by type of economic activity in the "Mining and Resource Extraction (MRE)" industry in 2023 shows that the leading positions are occupied by oil and natural gas extraction (44%), coal mining (16%), and mining of metal ores and others (29%), as well as provision of services in the field of mining - 11%. In value terms, the total volume of mineral extraction in the republic for the period 2006-2023 increased more than 10-fold, or from 119 to 1821 billion rubles, as shown in Figure 2.

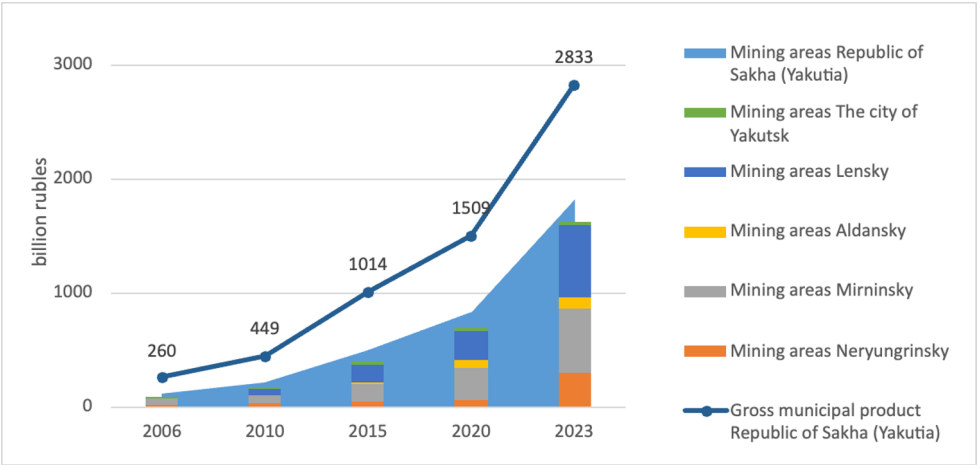

Fig. 2. Dynamics of mineral extraction (ME) and the share of the TOP-5 mining districts of the Republic of Sakha (Yakutia).

The share of the TOP-5 mining municipal districts (Mirninsky, Lensky, Neryungri, Aldansky, and the city of Yakutsk) also increased from 75% to 89% of the total shipped volume of domestically produced minerals in the republic.

As a result of industrial development in the region, the republic's exports increased significantly from 2006 to 2021, reaching $2.16 billion to $5.55 billion. These exports primarily consist of mineral products (36%) and natural diamonds (63%). Coal mining, natural gas, oil, platinum, nonferrous minerals, construction materials, and other minerals are extracted for domestic needs.

The prospects for industrial development of the republic (according to the data of industry strategies) are associated with the development of hard-to-reach mineral deposits, the development of transport infrastructure, and the implementation of large-scale energy projects in remote areas [10]. The development of the Arctic regions is primarily associated with the development of the Tomtor rare earth metal deposits and the expansion of diamond mining in the Anabar, Olenek, and Bulun districts. Active development of gold and tin mining in Ust-Yansky, as well as silver mining in the Verkhoyansky district, is planned. Comprehensive development is planned for coal mining in the Kolyma and Indigirka groups of districts. Thus, the Sakha Republic (Yakutia) has large-scale resources and prospects for

industrial growth in mineral extraction through pulse projects [11]. Their pace of development will be determined by the intensity of the provision of transport and energy infrastructure, subject to investment support and the implementation of modern resource-saving technologies. It is the technologies used for mineral extraction that have a key impact on the use of water resources in the areas of operation.

1.2 State of water resources in the districts of Yakutia

The most significant indicator for analyzing water resource conservation is water withdrawal from natural sources. The dynamics of water withdrawal from natural sources in Yakutia are shown in Figure 3. Overall, in the Republic of Sakha (Yakutia), water withdrawal from natural sources increased by 2.16 million cubic meters between 2010 and 2023, or by an average of 0.166 million cubic meters per year.

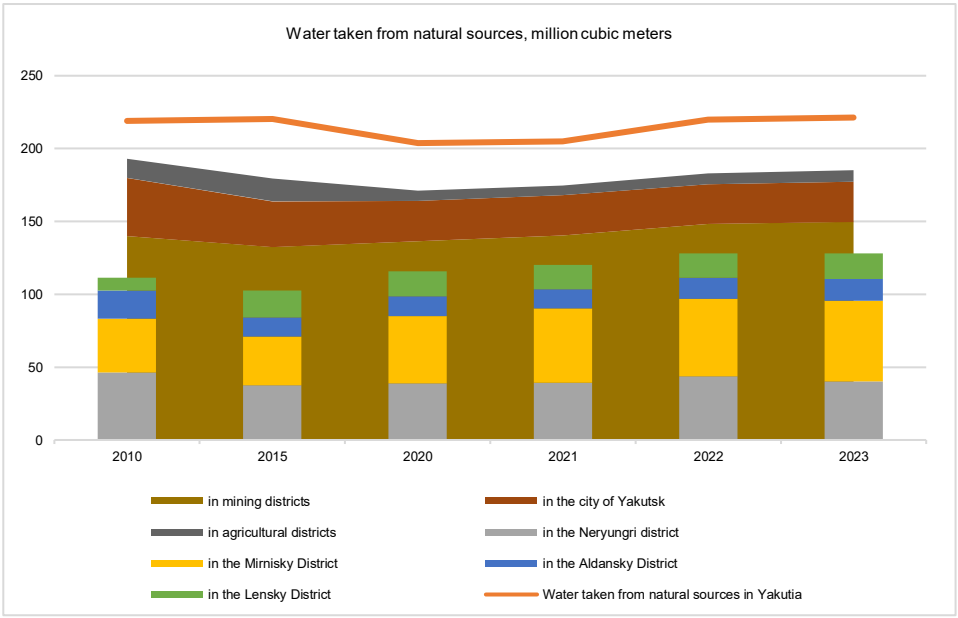

Fig. 3. Dynamics of water intake from natural sources and the share of the TOP-5 producing districts of the Republic of Sakha (Yakutia).

It should be noted that the distribution of this indicator across municipal districts is extremely uneven, but stable over time. This constancy is a negative factor in terms of water resource conservation.

A time series analysis revealed a trend toward increasing water withdrawal from natural sources by mining regions by the end of 2023 (+13% compared to 2015) due to the increasing dynamics of gold production amid growing global demand. At the same time, a downward trend in water withdrawal is observed in agricultural regions (-5.2% compared to 2015) due to a decline in agricultural production in the northern territories. It is noteworthy that water withdrawal has decreased in the city of Yakutsk (-12.6% compared to 2015), despite an increase in the urban population (+17% compared to 2015). The city concentrates about 38% of the republic's population.

2 Assessment results and forecast models

The research algorithm was implemented in stages: data collection, processing, evaluation, analysis, interpretation, and visualization of the results. Two-level modeling using the maximum likelihood method was used for data analysis. Districts were distributed based on territorial and administrative divisions within the republic, grouped by economic sector.

The following key water consumption indicators were used as a basis: water abstraction from natural sources (P1), volume of polluted wastewater discharged to surface facilities (P2), transportation losses (P3), use of fresh water for industrial needs (P4), use of fresh water for domestic and drinking needs (P5), and emissions of pollutants into the atmosphere from stationary sources (P6). Aggregated indicators were also used: water availability to the population (P7), share of polluted wastewater in the total runoff volume (P8), water consumption per unit of GMP (P9), water resources productivity (P10), and the integrated indicator of impact on water resources (P11).

2.1 Forecast assessment of water resources of Yakutia

Since there is no overall upward or downward trend for water intake from natural sources in Yakutia, it is reasonable to assume that, if the current trend continues, water intake volumes in 2025–2026 will remain at 217 million cubic meters per year, as shown in Table 1. To calculate the forecast for P1 and P2 indicators at the district level, adaptive forecast models with the highest level of reliability were constructed.

Table 1. Predictive assessment of water resource use indicators in the districts of Yakutia.

Districts	Water intake from natural sources		Volume of polluted wastewater discharged into surface waters	
	Forecast model	Forecast for 2025-2026, mill. cubic meters	Forecast model	Forecast for 2025-2026, mill. cubic meters
Republic of Sakha (Yakutia)	$\overline{y_t} = \bar{y}$	217.3-217.4	$\overline{y_t} = y_t + \overline{\Delta_{2020-2023}}$	90.5-93.7
the city of Yakutsk	$\overline{y_t} = y_t + \overline{\Delta_{2020-2023}}$	27.4-27.3	$\overline{y_t} = \overline{y_{(2019-2023)}}$	19.9-19.9
Neryungri	$\overline{y_t}$ = 130.24t² – 2369.5t + 49310	44.7-46.7	$\overline{y_t}$= 2062.3t + 2976.2	21.5-23.6
Mirninsky	$\overline{y_t}$ = -29.22t² + 2571.3t + 26770	60.4-62.0	$\overline{y_t}$ = -307,21t + 12293	9.5-9.2
Aldansky	$\overline{y_t}$ = 41.949t² – 1004.7t + 20545	15.2-15.6	$\overline{y_t}$ = 43.56t² – 1307.6t + 15678	5.9-6.0

The results of the time series dynamics of wastewater discharge volumes in the Republic of Sakha (Yakutia) for the period 2009-2022 showed a downward trend, where the average absolute increase was -1.15 million cubic meters with an average growth rate of -0.56% per year. In terms of wastewater pollution, the Republic of Sakha (Yakutia) is consistently ranked in the second group, where the share of polluted wastewater fluctuates between 33 and 66%. Consequently, we can speak of an increasing environmental load on water resources, i.e., they have a medium level of impact on water resources. This is primarily due to the local impact of industrial facilities in significant economically undeveloped areas. At the same time, Yakutia has seen a steady trend of decreasing water losses during transportation (P3)

from 17.4 to 6.1 million cubic meters (-65% by 2023) due to the implementation of resource-saving measures, which is typical for the country as a whole.

2.2 Grouping of districts by level of ecological and economic impact

From the perspective of water resource impact analysis (P11), it is crucial to study the municipal structure, identifying the most water-intensive industries (grouped by industry specialization). It should be noted that the distribution of Yakutia's districts by P11 is clearly differentiated, as shown in Figure 4.

In general, the integral indicator P11 was calculated using formula 1.

$$P11 = 0.123\ P9 + 0.120\ P7 + 0.172\ P8 + 0.133\ P6 + 0.148\ P3 \quad (1)$$

The key points in the P11 dynamics transition were as follows: 7 districts improved their positions by reducing their negative impact on water resources by lowering P3 and P6. The obtained P11 values for the period from 2010 to 2023 revealed that 11 municipal districts experienced significant growth. For example, in the Verkhoyansky, Nizhnekolymsky, and Oymyakonsky districts, the integrated indicator increased by more than 30%, indicating a significant reduction in the impact on water resources.

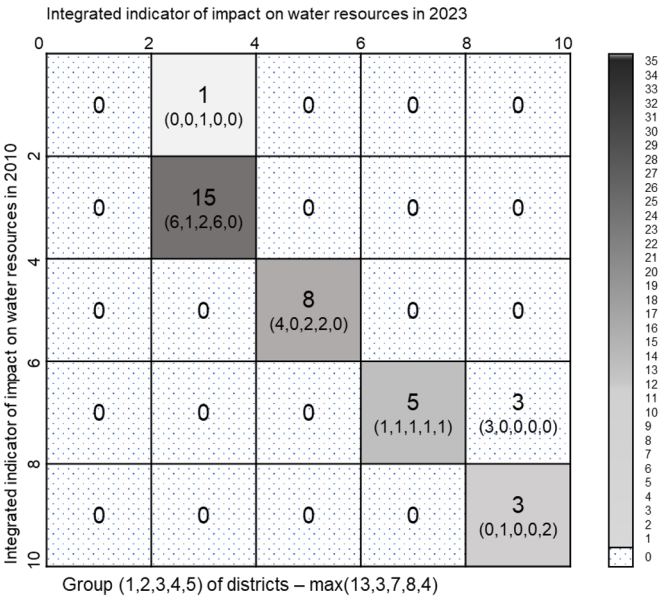

Fig. 4. The matrix of transition of Yakutia districts by the level of the integral indicator of impact on water resources for the period 2010-2023, taking into account their grouping by industry specialization.

At the same time, 10 municipal districts, on the contrary, showed a negative trend of declining indicator values, resulting in increased impact on water resources. Among the extractive groups, the Vilyuysky, Olekminsky, and Ust-Maysky districts saw their integrated indicator values decline by more than 30%.

3 Conclusion

Overall, the study yielded scientific results aimed at developing a tool-based justification for regional and industry-specific impacts on water resources in the region. The methodological tools and integrated approach to achieving the study's objective led to the following conclusions:

- It was revealed that the level of environmental and economic impact on water resources in the municipal districts of the Republic of Sakha (Yakutia) is quite unstable and chaotic. Water use and withdrawal from natural resources in the republic remains stable in volume, while the national average is declining [12].
- The study of the region's municipal structure, with an emphasis on identifying the most water-intensive industries, makes it possible to classify districts based on the types of industries that predominate in gross production. This grouping of districts allows and requires a differentiated approach to regional policy in the area of resource-saving measures and lean manufacturing.
- The practical significance of the results lies in the development of computational algorithms for multi-level modeling and forecasting of water consumption and the environmental and economic impacts on water resources in districts and the republic as a whole. The combination of cluster and multi-level modeling enabled a comprehensive study of the problem under consideration. The use of modern algorithms and models for processing empirical data ensured increased validity, reliability, and practical significance of the obtained results.
- A promising direction of research is to refine this computational algorithm with the functionality of situational modeling during the launch of new or liquidation of industrial facilities in areas taking into account the impact of external factors in northern territories.

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