УДК 332.122
https://doi.org/10.35567/1999-4508-2026-5-20-45
Original paper

Water supply and quality of water resources as determinants of regional industrial safety of the South of Russia

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ABSTRACT

Relevance. Among the most important conditions for achieving technological leadership of Russia there is industrial and water safety, high correlation and reciprocal influence of which form the basis for environmental safety; the state of water supply and water quality being internal challenges to sustainability. Sufficient water supply and high quality of water resources are conditions necessary for stable functioning of industry. **Methods.** Taking into account complementary nature of links between industrial and water sectors, logics of decision-making in the sphere of industrial safety is presented as gradual expansion of management focus: from rational decision-making to process-based, systematic and resource-complementary approaches, and then to digital transformation of management based on data, models, and knowledge to develop a concept-theoretic basis and tools for assessing the state of water resources **Results.** A concept-theoretic framework for the study has been developed, and search for ways and mechanisms to overcome the potential limiting effect in the system of industry-water resources has been carried out; the theory of industrial and environmental safety has been developed in conjunction with the concept of rational water consumption. The methodological diversity of approaches to assessing water availability has been emphasized and the use of neural network modeling has been proposed to determine enhanced evaporation losses from reservoirs of the Don, Kuban, Samur, Terek river basins. It has been determined that the obtained values of losses coupled with the high load on water bodies of these territories become one of the main destabilizing factors affecting the industrial sector of the macro-region through limiting the guaranteed water intake, deteriorating technical water quality, decreasing shipping capacity and increasing environmental restrictions for wastewater. The analysis of quality of water resources in the South of Russia has revealed technological and legal risks for industrial safety. There has been proposed a conceptual model based on three prerequisites: a reciprocal relationship between industrial and environmental safety, bilateralism between water and industry, use of updated estimates of water supply; with enhanced evaporation losses from the water surface, quality of water resources and specifics of the region considered.

KEYWORDS: industrial safety, water consumption, water supply, quality of water resources, complementarity of relations in the system of industry-water resources, regions of the South of Russia.

FOR CITATION: Matveyeva L. G., Kosolapova N. A., Papushenko M. V., Golovacheva M. M. Water supply and quality of water resources as determinants of regional industrial safety of the South of Russia. *Water Sector of Russia: Problems, Technologies, Management*. 2026. No. 5. P. 20–45; https://doi.org/10.35567/1999-4508-2026-5-20-45; EDN: SSZXXU

INTRODUCTION

In the National Security Strategy of Russia, which is focused on achieving sovereignty and technological leadership of this country in the global economic space, the leading role is assigned to industry - the key driver of the development of other sectors, as well as the entire Russian economy. Sustainable high-tech development and strategic security of industry constitute a key indicator of Russia's competitiveness. Achieving leading positions in its priority sectors will ensure further strengthening of the country's defense capability and attaining national development goals, create conditions for increasing the international authority of the Russian Federation and making cooperation with it more attractive to other countries[1]. Basic national industries, including hydropower and its water management complex, perform system-forming functions in the domestic economic management, provide the economy with the necessary means of production and primary energy resources, create conditions for its stable functioning, and exert a significant impact on the stability of budgetary and investment flows.

The role of industry and hydropower extends far beyond these sectors as they create the "energy basis" for the development of all regions of the country by performing the afore-mentioned functions. This is particularly evident in the context of the new global system, which at the current stage is not only a geopolitical and geo-economic driver of transformations taking place in the global economy, but also a product of the digital revolution defining new paradigms for developing the domestic industry. Among these is the concept of industrial and energy (including environmental) safety, based on digital technologies, as a key condition for national security and stability. At the same time, a high correlation between industrial and environmental safety is evident, as well as their reciprocal influence: industrial safety forms the foundation of environmental safety, within which the state of water supply and water resources quality act as internal challenges to environmental sustainability. On the other hand, sufficient water supply and high quality of water resources are a necessary condition for stable and safe functioning of the country's industrial complex and its regions.

High water supply is more characteristic of the northern and Far-Eastern regions of the Russian Federation, while in the southern regions of Russia water supply coefficients of the economy take on minimal values [1]. Given this situation, it be-

1 The National Security Strategy of the Russian Federation. Decree of the President of the Russian Federation dated July 2, 2021, No. 400.

comes clear that the risk of destabilizing industrial safety is increasing. The main strain on water resources of the southern regions is exerted by the agricultural sector, so increasing the level of water resources supply in the southern industrial hub is possible precisely through improving efficiency of water use in agriculture, which is noted in publications not only by Russian, but also by a number of foreign scientists [2]. Since industry is one of the main consumers of water in terms of volume, the shortage of water resources acts as a limiting factor for production capacities and a cause of reduced technological reliability of facilities, especially during periods of low water levels. As a result, there arises a certain "vulnerability" of industrial facilities and the conflict of interests between entities in various sectors of the economy, which intensifies during periods of low water levels, worsens the problem.

The above problem is also aggravated by deteriorating quality of water resources. According to the Federal Service for Hydrometeorology and Environmental Monitoring data on the assessment of surface waters quality in the Russian Federation [3], as of 2024, water quality in the regions of southern Russia is characterized by pronounced territorial heterogeneity and a variety of pollutants. The Rostov region is reported to have a high degree of pollution (the 5th class of quality – "extremely dirty" water), while a low degree of pollution – the 1st class quality ("relatively clean" water) is typical of the regions with the maximum number of gauging stations - the Republic of Crimea and some water bodies of the Krasnodar Territory, the Karachay-Cherkess Republic and the Republic of North Ossetia-Alania. Such territorial water quality heterogeneity in regions of southern Russia poses a threat to industrial safety as more developed industrial regions are characterized by low water quality, which leads to increased costs on water treatment to meet standards required by technological processes, as well as limitations on the choice of modern technologies directly related to water quality, increased risks of accidents and downtime due to equipment corrosion, difficulties in complying with discharge composition standards, and a decline in investment attractiveness [4]. At the same time, regions having water quality of a higher class are characterized by more challenging (climatic and topographic) conditions to build large-scale industrial complexes, which may result in a slowdown in the industrial development of regions of southern Russia.

In this context, it should be noted that the list of the main mechanisms for implementing state policy in the field of ensuring environmental safety does not only include appropriate assessment of development projects and programs of the Russian Federation and its regions, but also expertise of industrial safety[2] and comprehensive modernization of the production and technological base of real economy sectors; requirements of industrial and environmental safety[3] included. Thus, at the state level, firstly, close connection between industrial and environmental safety is

2 Decree of the President of the Russian Federation dated April 19, 2017, No. 176 "On the Strategy of Environmental Safety of the Russian Federation for the Period up to 2025".

3 Decree of the President of the Russian Federation dated May 13, 2017, No. 208 "On the Strategy of Economic Safety of the Russian Federation for the period up to 2030".

emphasized; secondly, it is demonstrated that modernization of the production and technological base of real economy sectors, which is necessary for their sustainable growth, is carried out precisely meeting the requirements of industrial and environmental safety.

In accordance with this, taking into account obvious complementarity of links between industrial and water management sectors of the economy, the logic of decision-making in the field of industrial safety can be presented as a sequential expansion of the so-called management focus: from rational and precise decision-making to classical process-based, systemic and resource-complementary approaches, and further to digital transformation of management based on data, models, and knowledge. At the same time, it is digitalization that has become a new round in this evolution: it restructures connections between previously established approaches shifting management from local automation to data-based end-to-end process control [5].

Recent publications have noted that transition of water management complexes to new industrial forms based on large-scale digitalization is becoming particularly important in the current context, when hydropower as a component and a dynamic profile of the region's industrial landscape [6] functions in upgrading the structure of regional economies, enhancing the potential for high-tech development, and ensuring balanced development with the help of circular business models [7]. It should be emphasized that the state of water resources is also an integral part of this transition as their exhaustibility and heterogeneity have a direct impact on technological regimes of industrial water use, uninterrupted operation of industrial complexes, and increased resilience to external shocks. In the context of achieving technological leadership for Russia and its regions, the role of high-tech industrial enterprises is conceptualized primarily through their special strategic significance as key agents of structural transformation of the economy: it is they that form the basis of the import-substituting circuit in industry, ensure the growth of export potential, and create a multiplicative effect for related industries [8]. The functional role of high-tech enterprises in the new economic model is not limited to the production of knowledge-intensive products, digitalization of industry acts as a factor changing the spatial and sectoral structure of the region; with high-tech enterprises playing the role of diffusion points for technological innovations into related industries. For spatial and sectoral transformation, the state of water resources may become a critical limiting factor of a dual impact: on the one hand, it can serve as a possible stimulus, and on the other hand, as a potential constraint. The stimulating effect is evident when implementing water-saving technologies, including the ones in agricultural and industrial sectors, and in transition to circular water use models; the limiting effect is observed when there is a shortage of water of a low contamination level leading to higher costs on water treatment, which reduces either the efficiency of existing high-tech facilities or investment attractiveness of establishing new production facilities.

According to the authors, in this context, methodological and practical interest lies in a scientifically grounded search for ways and mechanisms to overcome the potential limiting effect, which is directly related to understanding water supply and water resource quality as key determinants of industrial safety of regions.

RESEARCH MATERIALS AND METHODS

Regional water resources playing a priority role, versatility and multidimensionality of industrial safety issues presented above explain the interdisciplinary nature of the study based on the joint consistent use of a whole range of interrelated theories and concepts, such as theories of spatial development and location of productive forces, territorial and industrial development, resource efficiency, structural transformation of regional systems, a new economic geography, the concept of modernizing industrial production based on digitalization innovations, institutional economics, and others. This is predetermined by the highest priority given to the strategic development of industry and the need for its regional regulation as a hierarchically nested system that determines involvement of entities in the country's industrial policy. At the same time, according to a large number of scholars (A. E. Kosolapov, N. A. Kosolapova, L. G. Matveyeva, E. V. Kaplyuk, and others), the region's industrial sector should be considered together with natural and climatic factors including water resources of the territory. Modern studies in the field of interconnected research into industrial and water sectors of a region treat them as an interdependent system in which management decisions in one sector generate spillover effects in related sectors of water management, with a focus on finding compromises between these sectors. To develop this idea, the authors put forward and test a hypothesis that industrial security is achieved by forming a stable configuration of links between the above-mentioned regional economy sectors aimed at the efficient use of limited water resources. Within the framework of this concept, there is considered joint application of a systemic, resource-oriented, and resource-complementary approach, as well as the concept of resilience to make a typology of management regimes ensuring the maximum synergistic effect and identify factors limiting achievement of industrial safety sustainability in the region.

The methodological framework addresses the issue of rational use of the region's water resources in the context of industrial safety concepts, as well as conceptual determination of interconnected and entangled development of the region's industrial and water ecosystems. This is ensured by the interrelation of mechanisms and strategies for their development at different hierarchical levels.

Industrial production has a significant impact on the level of water consumption due to its higher water intensity compared to other types of economic activities, but it also has a high energy-saving potential, which depends on the technologies used. In addition to analyzing the impact of technological changes, there is a question regarding significance of labor productivity in industry and structural changes in the

industrial sector in the overall influence of these factors on the intensity and efficiency of water consumption. Nonuniformity historically established in the sectoral structure of regional economies only increases the relevance of such studies. In this context, significance of these tasks is determined by the impact of water supply policy not only on the competitiveness of industrial sectors and industrial security, but also on the balance of water resource, industrial and socio-economic development in the region.

It should be noted that interconnection, interdependence, and mutual influence between industrial and water ecosystems determine the importance of a special study of the problem of managing effective water supply for the industrial development of a region within the strategic imperatives of innovation and digitalization. Results of numerous studies allow us to state that the main causes of existing problems in the system of water supply for the industrial development of the region are as follows: first and foremost, this is the unbalance between the current economic mechanism for distribution and use of water resources in this sector, financial capabilities of water users and the system for managing use and protection of water resources and their actual potential; as well as the lack of coordination between water use strategies of industrial systems at different hierarchical levels.

The range of industrial sectors represented by water-consuming enterprises in the region is quite diverse and generally corresponds to the region's specialization, as well as to the level of development of its business and infrastructure sectors. Depending on the industrial development policy at the regional level, it may be necessary to provide priority support to certain industries as the foundation for effective functioning of the entire regional reproduction system.

In the current context, rationality of water use is expressed in achieving the greatest possible balance between existing needs and actual supply of water resources to economic entities. In the strategic context, the existing dynamics of sectoral water intensity in the region becomes important as it determines the key benchmarks for forecasting future water needs of the region's economic entities.

The high level of water intensity in industrial production, which has been verified in the course of the study and is characteristic of Russian enterprises under current economic conditions, determines the need to improve rationality of water use in order to strengthen competitive positions of regional economies. The critical level of pressure on water resources is a constraint for socio-economic development of a territory simultaneously posing a threat to environmental and industrial safety. In recent years, an increasing number of scientists studying the issues of the rational distribution and use of water resources have placed a particular emphasis on the need to use the indicator of water intensity of GRP in regional strategy planning. This is due to the fact that this approach makes it possible to assess the level of use of water-saving technologies in the region and possibility of intensifying factors of regional industrial production while preserving integrity of water management systems.

Thus, taking into account objectively established complexity of the modern water use system and a need to implement various approaches to water resources management adapted to the specifics of a particular water basin and the industrial ecosystem of the region, it is necessary to improve decision-support tools in this sphere.

The authors suggest using classical approaches to quantitative calculations together with modern methods of neural network modeling to make an a more refined and regular evaluation of water supply in the regions of Southern Russia.

The values obtained with neural network models for detecting water on satellite images (the DeepWaterMap convolutional neural network) and the areas of water bodies (the EfficientNet–MANet transformer neural network) make it possible to determine enhanced evaporation loss from water bodies [9]. The areas of water bodies were determined using Earth remote sensing data from the Landsat spacecraft series for the Don, Kuban, Samur, and Terek river basins, which belong to the macro-region under study. The choice of this source is determined by regularity of surveys and its large coverage area. To ensure a complete coverage of the basins of the specified rivers, there were used data for 2018–2024 fully covering the area under study. To estimate the maximum possible enhanced evaporation loss from the water surface, there were taken maximum areas of water bodies where an overlap was observed. To calculate enhanced evaporation loss from the water surface, there were selected data on the average long-term layer of evaporation from the water surface during the warm period from the 5th to the 9th month inclusive based on the GGI-2000 evaporimeter [10], as well as on the average long-term layer of adjusted precipitation values, with systematic errors of precipitation gauges eliminated, based on observational data for the same period[4]. The choice of this time period is determined by the fact that the volume of evaporation during cold months (from November to March) is either negligible or its accounting requires special methods (for example, for snow cover), which are not included in standard calculations for water bodies.

Using geo-information software tools, values of the average long-term layer of evaporation from the water surface and adjusted precipitation values were interpolated; systematic errors of precipitation gauges eliminated with the inverse scaled distance method. The volume of precipitation and surface evaporation was determined for the water bodies in the Don, Kuban, Terek, and Samur river basins; their average evaporation surface identified with the neural network. This was implemented using an algorithm that allows assigning the values of adjusted precipitation and evaporation from the water surface to each of the identified river basins based on their coordinates. Shape files containing the areas of the basins and interpolated values of the indicator (adjusted precipitation, evaporation from the water surface)

4 All-Russian Research Institute of Hydrometeorological Information - World Data Center (VNIIGMI-MCD). [Electr. resource]. URL http://meteo.ru

are overlaid in layers based on coordinates. The indicator value is assigned to the basin at the point of intersection. If the basin crosses several values of the indicator, its average value is assigned. Based on the data obtained, enhanced evaporation losses from the water surface were calculated for the areas of the water bodies at their maximum filling, and the potential impact on the industrial sector of the regions of Southern Russia was demonstrated.

To characterize quality of water resources in the regions of Southern Russia, data from "Surface water quality of the Russian Federation: yearbook" [3] were used. Based on these data, the state of the quality of water resources in the regions of Southern Russia was assessed, and possible risks to industrial safety were identified.

On the results of the empirical analysis, the authors propose a conceptual model of interconnection of water resources quality, water supply and industrial safety of the regions of Southern Russia.

RESULTS AND DISCUSSION

According to the resource-complementary approach adopted by the authors, competitiveness of a regional economy is becoming less determined by an access to natural resources available, particularly water resources, and more determined by the ability to generate and integrate them with technological innovations leading to a synergistic effect. L. V. Glezman substantiates that it is technologically complex production processes in line with the logic of resource complementarity with natural resources that determine spatial and sectoral specialization of a region and act as centers that attract skilled personnel and investments [11].

The industry of Southern Russia is a powerful agro-industrial, energy, and mechanical engineering complex; the main players being food industry, agricultural machinery manufacturing, fuel and energy sector, as well as metallurgy and production of building materials. The total revenue of 300 largest industrial enterprises in Southern Russia increased by 10 % from 2022 to 2025, but their total profit more than halved. The region's industry demonstrates moderate dynamics and a high dependence on the agro-industrial complex. Processing industries and agriculture remain the main drivers of stability for the southern regions, the Krasnodar Territory included.

The largest water users in the south of Russia, which submit reports on water use in the 2-TP (water management) form, are enterprises in the power industry, oil production, chemical industry, and agro-industrial complex (Table 1).

For example, by the end of 2025 manufacturing industries retained their leading position in the economic structure (table 2) in the Rostov Region, one of the leading regions in the south of Russia (fig. 1), which, as noted above, is characterized by high water consumption due to specifics of agricultural production.

Table 1. The volumes of water use by major enterprises water-users [5]

Enterprises	Water volume, mln. m³	
	Diversion capacity	Discharge water
LLC "LUKOIL-Ecoenergy" (Belorechenskaya Hydroelectric Power Station)	1768,15	0
Branch of PJSC "OGK-2" - Stavropol State District Power Plant	1613,22	1612,82
Branch of PJSC "RusHydro" "Cascade of Kuban Hydroelectric Power Stations" (Stavropol Territory)	966,61	0
LLC "LUKOIL-Kubanenergo"	162,5	157,49
Branch of JSC "Concern Rosenergoatom" – "Rostov Nuclear Power Plant"	120,26	55,72
JSC "KAUSTIC"	58,62	42,97
LLC "APK ASTRAKHANSKY"	16,67	0,6
Southern Branch of LLC "Gazprom Energo" (Southern FGPE)	15	3,99
LLC "LUKOIL-Nizhnevolzhskneft"	15,97	12,94

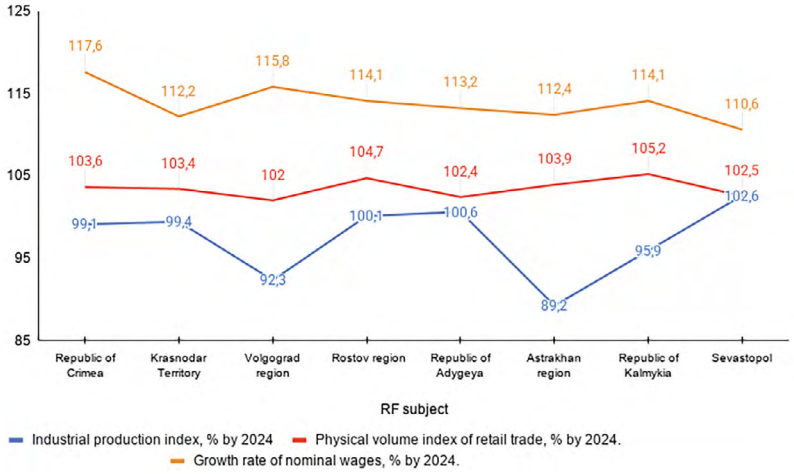


Fig. 1. Comparative indicators of industrial development of the South Federal District constituent members, January – December, 2025[6]

Table 2. Indices of production and the volume of factory shipments for some high-tech types of activities of the Rostov Region, January – December, 2025[7]

Activity category	Production index, % by 2024	Volume of factory shipments, mln. rub.	% by 2024
Manufacturing industries, total	100,7	1 492 320,2	95,9
Production of other vehicles and equipment	114,6	160 667,7	113,7
Production of machinery and equipment	106,4	105 572,0	81,5
Production of electrical equipment	104,8	57 536,2	112,3
Production of computers, electronic and optical products	83,0	45 059,8	94,9

The Rostov Region is among the South Federal District regions having positive dynamics in industrial production (100.1 per cent) and the highest growth in retail trade turnover (104.7 per cent), which indicates relative stability of the economy.

5 Compiled by the authors on the basis of data from form 2-TP (water management).
6 Compiled by the authors according to Rosstat data.
7 Economic and social indicators of development of the Rostov region in January – December 2025 / Rosstat. Rostov-on-Don, 2026. [Electr. resource].URL: https://61.rosstat.gov.ru/storage/mediabank/i2608033.pdf

At the same time, the wage growth rate (114.1 per cent) is lower than in the Republic of Crimea (117.6 per cent) and the Volgograd Region (115.8 per cent). In the context of competition for technological personnel, it creates additional pressure on high-tech enterprises of the region.

The innovative component of the regional industry also shows positive dynamics: the volume of producible innovative products amounted to 240.0 billion rubles, and the specific weight of enterprises using technological innovations was 50.3 per cent[8].

At the same time, the analysis of these indicators reveals a number of structural limitations (Table 3). According to comparative data in the context of the subjects of the Southern Federal District, the Rostov Region in 2025 is included in the group of regions with an industrial production index above 100 per cent (100.1 per cent) and an advance growing rate of wages (113.9 per cent against the average for the Southern Federal District 113.4 per cent)[7].

Thus, high-tech production makes a significant contribution to the competitiveness of the economy of the Rostov Region and the South of Russia as a whole.

Table 3. Structural limitations of the high-tech sector of the Rostov region

Parameter	Actual state	Identified limitation
Demand structure	Production of vehicles and equipment (defense industry) – growth of 114.6 %; production of computers and electronics – decline to 83.0 %	Dependence on defense orders, civil high-tech segment being weak.
Export potential	Volume of non-resource, non-energy exports – $ 4,800 million against the target of $ 8,720 million	Shortfall of export targets by 45 % due to a decline in food exports and weakness of industrial exports
Digital maturity of industries	The indicator of 68.2 % was achieved mainly due to public administration and the social sector	Uneven distribution of digital maturity across industries and size groups of enterprises
Innovation activities	50,3 % of organizations made technological innovations	A gap between large defense industry enterprises and medium-sized technology businesses in terms of innovation activity level.

Table 4. Comparison of technological intensity levels and production dynamics in terms of high-tech types of activities of the Rostov Region, 2025.[9]

Activity category	Average monthly salary, rub.	Production index, % by 2024	Volume of factory shipments, bln. rub.	Volume dynamics, % by 2024
Production of computers, electronics, and optics.	100 616,8	83,0	45,1	94,9
Production of other vehicles	96 277,1	114,6	160,7	113,7
Production of machinery and equipment	91 660,4	106,4	105,6	81,5
Production of electrical equipment.	90 728,1	104,8	57,5	112,3
Production of chemicals	85 392,3	116,8	59,2	109,0
Manufacturing industries, total.	84 275,9	100,7	1 492,3	95,9

8 Report on the implementation of the Rostov Region State program "Economic Development and Innovative Economy" for 2025. [Electr. resource]. URL: https://www.donland.ru/result-report/2808/

9 Compiled by the authors according to Rosstat data.

The analysis of table 4 allows us to identify several empirically significant patterns and apply the identified patterns to the sectoral structure of water consumption and wastewater discharge. First, industries having the highest level of labor remuneration (computers and electronics – 100,616.8 rubles) demonstrate negative dynamics in the physical volume of output (83.0 per cent), which indicates a cyclical rather than structural nature of their production activity and dependence on government orders, and, as a result, minimizes the anthropogenic load on water bodies. Secondly, segments of diversified demand show the most stable growth: chemical production (116.8 per cent) and vehicle manufacturing (114.6 per cent) are associated with increased water consumption and higher risks of discharging highly toxic pollutants. Thus, sectoral economic growth to some extent conflicts with indicators of the state of water resources making monitoring a critical factor for sustainability of industrial clusters as depletion of assimilative capacity of water bodies neutralizes positive macroeconomic effects and causes long-term man-made risks.

There are several approaches to assessing water supply which include examining this indicator in the context of territorial division - territorial water supply, and in the context of consumer needs – public water supply, as well as water supply at the economic level – "the ratio of river flow resources to freshwater withdrawals" [1]. Researchers often resort to using classical mathematical tools, statistical analysis, a criterion-based approach, and mapping; data sources for assessment are the Federal State Statistics Service, the Federal Service for Hydrometeorology and Environmental Monitoring, research institutes, and basin water management authorities, as well as Earth remote sensing. At the same time, analysis of domestic and foreign sources made it possible to identify the multifaceted nature of methods for assessing water supply.

Thus, the classical approach involves calculating indicators of water supply in territories as the ratio of the amount of resources to the area under consideration and water supply to the population as an integral characteristic determined by the amount of water resources in relation to the population size in the region under study [12]. The first indicator is unable to reflect the real level of water resource supply in the regions of southern Russia due to the lack of geographical and climatic characteristics, as well as the specifics of sectoral water consumption. Water supply in the territories may lead to an overestimated resource well-being in the water sector in southern Russia due to the presence of regions of mountainous terrain, while the main industrial clusters are located in flat regions having high anthropogenic pressure. In this regard, many researchers use a specific indicator – public water supply, which correlates with industrial water consumption and makes it possible to rank regions of southern Russia by water supply. However, this indicator cannot be considered as a universal predictor. Firstly, it does not take seasonality into account, which is particularly important when assessing water supply as there are significant differences in the areas of water bodies during the flood and low-water periods; sec-

ondly, in the context of global warming, which causes increased evaporation losses, and a high risk of water stress as one of the climate risks [9], it leads to overestimation of water resources supply. The indicator of public water supply is also supplemented by calculating efficiency and sustainability of water supply [13] forming a multi-level assessment system that makes it possible to make simultaneous evaluation of several independent but interrelated parameters. The system determines the position of the regions of southern Russia in terms of the level of water supply.

In the scientific community, such methods of assessing water supply as the use of geo-information technologies and Earth remote sensing data [14] have become particularly widespread; with high spatial discreteness, they allow for spatial modeling of water balance elements, including precipitation, evaporation, and runoff volumes. Vegetation index indicators (NDVI, NDDI) and meteorological drought indices (SPI, AI) serve as a complement and make it possible to refine water supply in semi-arid regions of the Russian Federation, some of which are part of the regions of southern Russia. Today, there is often used a multi-criteria approach integrating hydrological, climatic, geographical, and socio-economic measurements, which is especially relevant for the regions of southern Russia. Combining these approaches and implementing modern neural network modeling tools will make it possible to refine assessing water supply in the regions of southern Russia in real time, which will help reduce time costs and increase adaptability of decisions made and, consequently, diminish risks for industrial safety.

The describable methodological diversity may lead to an ambiguous interpretation of the actual state of water supply in the regions of southern Russia and result in making ineffective management decisions, which will directly affect the state of the industrial sector. In many studies, the shortage of water resources is attributed to the negative impact of industry, which, as one of the largest participants in the water management complex, consumes large amounts of fresh water, thereby increasing the problem of water scarcity and contributing to deterioration of water resource quality. This aspect cannot be ignored, but it is worth noting that there is another interconnection: a threat to industrial safety is generated by water scarcity and poor water quality in the regions of southern Russia. This leads to deteriorating of both extensive and intensive production factors. In terms of extensive factors, there is a reduction in the volume of water resources as a raw material, and an increase in capital investments that are not related to improving core technologies but aimed at maintaining a minimum level of water supply. The impact on intensive factors is exerted through reducing efficiency of technological processes, in particular their slowdown, deteriorating properties of the finished product, inhibition of the intensive renewal of fixed assets due to increased physical wear and tear of equipment, and an increase in the resource intensity of production. In this regard, it can be concluded that in the macro-region under study, there is a threat of forming a destructive pattern in the industrial sector via water resources. Quantitative insufficiency in the

form of water shortages and unsatisfactory qualitative characteristics in the form of a high degree of pollution become not just operational costs, but a powerful disincentive to the intensive development of the industrial sector.

The regions of southern Russia are also heterogeneous in terms of the level of pressure on water bodies. For example, the Don and Kuban river basins are characterized by a very high and critical level of pressure on water bodies, this territory experiences a serious water deficit [15], while the Samur and Terek river basins have a more differentiated pressure on water bodies due to specifics of the mountainous terrain, but at the same time they are highly vulnerable to natural factors [16]. This, in turn, leads to a vulnerable industrial infrastructure and requires measures to improve water consumption efficiency in the Don and Kuban river basins. This can be achieved by increasing water consumption efficiency in the agricultural sector and reducing the level of competition among participants in water management complexes. It also leads to the need to place a special emphasis on seasonality – both for the Don and Kuban river basins and, in particular, for the Samur and Terek river basins, due to the torrential nature of the river and catchment systems having low buffer capacity. Based on the results of calculations of changes in the areas of water bodies in the basins of the Don, Kuban, Samur, and Terek rivers with the DeepWaterMap and EfficientNet–MANet neural networks [17] on data from Landsat-8 and Landsat-9 satellite images for the period of 2018- 2024, there is observed a decrease in the area of water bodies (with a water surface area > 0.025 km² as this area is insignificant in the context of modeling water balance) during the low-water period compared to the high-water period (table 5).

Table 5. Changing areas of water bodies in the Don, Kuban, Samur, and Terek river basins

River basin	Changes, %
The Don	−14
The Kuban	−59,76
The Samur	−32,36
The Terek	−7,56

Based on the obtained data on the area of water bodies, enhanced evaporation losses from the surface of water bodies were determined (table 6).

Table 6. Enhanced evaporation losses from water bodies **in the Don, Kuban, Samur, and Terek river basins during the warm period (5th – 9th months)**

River basin	Enhanced evaporation losses from water bodies, mln. m³
The Don	2800,8
The Kuban	666,23
The Samur	9,61
The Terek	95,8

At the same time, the maximum volume of enhanced evaporation losses comes from the water surface of rivers. This clarification allows us to conclude that there is a risk of increased water loss when water does not reach water intake structures

in the basins of the Don and Kuban rivers, for the Samur and Terek rivers the calculated values having a minimal impact on this due to the landscape characteristics. In addition to the above-mentioned high load on water bodies in the Don and Kuban river basins, the resulting values of enhanced evaporation losses from water bodies become one of the main destabilizing hydrological factors exerting a systemic impact on the industrial sector of the macro-region. This leads to limitations on guaranteed water intake, deterioration of industrial water quality, reduced shipping capacity, and increased environmental restrictions on discharged waters. This impact can be characterized as environmental and infrastructural, contributing to increased operating costs and reduced reliability of water supply to the industrial sector of southern Russia during the warm season.

Another determinant of industrial safety in the South of Russia is the quality of water resources, which is characterized by a high degree of pollution. Monitoring of water resource quality is not carried out on a regular basis: data are submitted to the closed net of "State Monitoring of Water Bodies" of the state information system "Digital Platform "Water Data" incompletely and untimely; the most detailed analysis of water resource quality at the regional level made by the Federal Service for Hydrometeorology and Environmental Monitoring once every two years. In this regard, there arises a problem regarding active assessment of the quality of water resources. However, only external negative technogenic factors contribute to fundamental changes, and in recent years, no positive trends have been observed in the macro-region under study. Thus, in 2024, in the Azov hydrographic region, the degree of water pollution ranged from class 1 to class 5 (from "conditionally clean" to "extremely dirty" water) [3]. It should be noted that classes 3 and 4 of water quality predominate (Fig. 2).

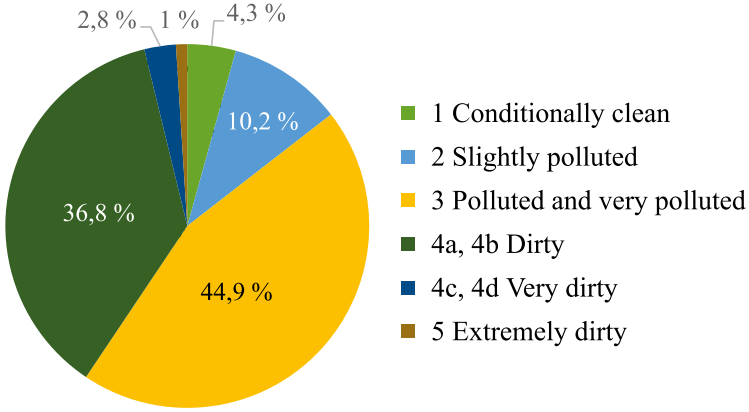


Fig. 2. The pollution degree of the Azov hydrographic area water bodies [3]

In the Terek River basin, prevailing of "polluted" and "very polluted" water is observed on most monitoring stations, with water of class 5 ("extremely dirty") quality being absent (Fig. 3).

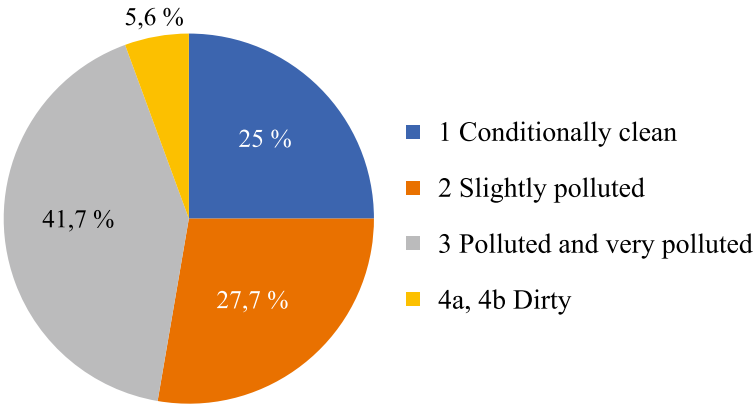


Fig. 3. The pollution degree of the Terek River basin water bodies [3]

In the water bodies of Dagestan, water quality varied from class 2 ("slightly polluted") to class 3 ("polluted" and "very polluted"). "Very polluted" water is characteristic of the Samur River basin, the only assessed in this region reservoir – the Chirkey Reservoir having water quality class 2 ("slightly polluted") [3].

The assessed state of water quality in the regions of southern Russia leads to systemic limitations on industrial water use. The anthropogenic impact on water bodies is increased by natural and climatic factors – low water levels, floods, and geochemical characteristics of the region. It should be noted that in the assessment of water quality made with the specific combinatorial index[10] regional characteristics of water bodies under study are not considered – this issue is reflected in many domestic studies.

The technogenic impact on the industry of the macro-region is associated with the most common polluting chemicals typical of this area (table 7).

The main sources of pollution are industrial wastewater, domestic sewage, livestock waste, and landfills in water protection zones, as well as reclamation projects and industrial facilities situated in water protection zones on the territory of Dagestan.

Table 7. The most widely spread pollutants of water bodies on the territory of the South of Russia [3]

Pollutants	The Azov Region	The Terek river basin	Dagestan
Organic fertilizer s(BOD $_5$/COD)	Systematic pollutant	27 examples	Typical of a lake
Nitrogen compounds (ammonium, nitrite)	–	2–11 MPC	–
Sulfates	–	161–189 mg/l	Up to 877 mg/l (lakes)
Copper compounds	Systematic pollutant	2 MPC (the New Terek)	1–2 MPC
Iron compounds	–	1–2 MPC	1–2 MPC
Petroleum products	Frequency of exceeding concentration up to 34,95 %	Single instances	–

10 Methodological guidelines. A method of comprehensive assessment of the degree of contamination of surface waters on hydrochemical parameters. Rostov-on-Don: Roshydromet, 2002.

A systematic analysis of the impact of this level of water resource quality on the industrial sectors of the macro-region indicates the emergence of the following risks to the industrial safety of southern Russia.

1. *Technological risks*. For such water-intensive industries as heat power engineering, chemical industry, metallurgy, and paper manufacturing, water of quality classes 3 ("polluted" and "very polluted") and class 4 ("dirty" and "very dirty") will lead to higher costs on water treatment as a high concentration of organic substances will require multi-stage treatment systems to meet quality standards for wastewater discharged into water bodies[11]. This will be accompanied by increased equipment wear due to accelerated corrosion processes caused by high concentration of sulfates and iron, as well as presence of copper as a systemic pollutant, which create an aggressive environment for heat exchangers and pipelines.

2. *Legal risks*. The Water Code of the Russian Federation sets an obligation to meet standards for permissible impact on water bodies[12]. Due to the current unsatisfactory water quality, the risk of violating these standards is increasing, which may lead to administrative and civil liability measures, restrictions on water use during low-water periods, and compensation payments for damage to aquatic biological resources.

These risks and current situation in the water sector determine a need for the industrial sector to implement closed-loop water recycling systems to reduce dependence on the quality of surface water and develop programs to improve efficiency of wastewater treatment facilities; for the scientific community and regulators - to expand the list of substances to be monitored in water bodies, to develop target water quality indicators taking into account regional specifics, and to approve them at the legislative level. The absence of such measures may lead to destabilization of industrial safety of the regions of Southern Russia and, as a result, become a barrier to the region's economic development.

CONCLUSION

Based on the above-mentioned principles, the authors propose a conceptual model based on three premises: a reciprocal relationship between industrial and environmental safety; bidirectional nature of the relationship between water resources and the industrial sector; and use of refined assessments of water supply, taking into account enhanced evaporation losses from water surface and quality of water resources; regional specifics considered (fig. 4).

11 Resolution of the Government of the Russian Federation dated July 29, 2013, No. 644 (as amended on November 28, 2021) "On Approval of the Rules for Cold Water Supply and Sanitary Sewage and on Amendments to Certain Acts of the Government of the Russian Federation".m;

12 Water Code of the Russian Federation dated June 3, 2006, No. 74-FZ (as amended on August 4, 2026). Water Code of the Russian Federation, Article 35. Development and establishment of standards for permissible impact on water bodies and target water quality indicators in water bodies

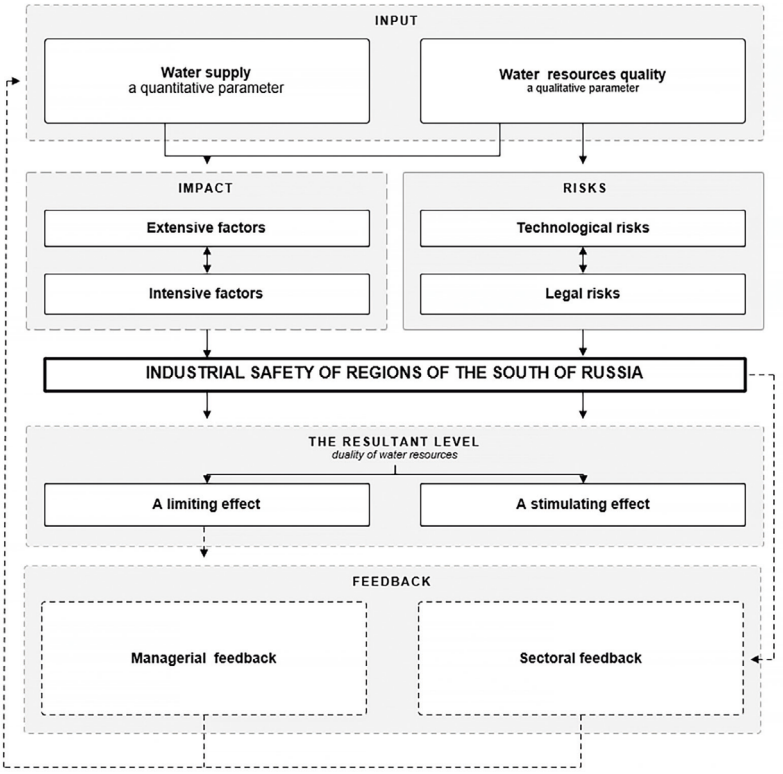


Fig. 4. Conceptual model of interconnection of water supply, water resources quality and industrial safety of regions of the South of Russia

The input circuit of the model includes quantitative (water supply) and qualitative (water quality class) parameters. There are two groups of factors affecting industry: extensive production factors - by reducing the volume of water resources as a raw material and increasing capital investments that are not related to improving basic technologies but aimed only at maintaining a minimum level of water supply; and intensive production factors – by reducing efficiency of technological processes, which manifests itself in their slowdown, deterioration of properties of finished products, and inhibition of the renewal of fixed assets due to increased physical wear and tear of equipment and an increase in the resource intensity of production. Separation of these factors is crucial for the model: influencing intensive factors means that water resources are not treated as operational costs but as disincentives to intensive development of the industrial sector. The quality of water resources in the regions of southern Russia leads to two types of risks: technological risks, which are typical of water-intensive industries, manifest themselves in higher costs on water treatment, a need of multi-stage purification systems, and increased equipment wear and tear; and legal risks are associated with a threat of administrative and civil liability measures, restrictions on water use during low-water periods, and compensation payments for damage to aquatic biological resources.

The combined effect of extensive and intensive influence determines the state of industrial safety in the regions of southern Russia, i. e. technological reliability and uninterrupted operation of industrial facilities are formed by the resultant level at which the duality of water resources becomes relevant, manifesting itself in a limiting effect when there is a shortage of water of a low degree of pollution, and in a stimulating effect when water-saving technologies are introduced, infrastructure in the industrial and agricultural sectors is modernized, and a transition to circular models is made.

The model is closed by two feedback relations: the first is sectoral, reflecting the direct impact of the industrial complex on the state of water resources; the second is managerial, formed as a response to the results achieved and including, for the industrial sector, implementation of closed-loop water recycling systems, programs of improving efficiency of treatment facilities, expanding the list of substances to be monitored in water bodies, and developing target water quality indicators tailored to regional specifics and adopted by law. The logic of this circuit corresponds to a progressive expansion of the management focus - from rational decision-making to process-based, systemic, and resource-complementary approaches, and further to digital transformation of management based on data, models, and knowledge that ensures a transition from local automation to end-to-end process control.

CONFLICT OF INTERESTS
The authors declare no relevant conflict of interests.

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Received 28.08.2026.
Revised 19.09.2026.
Accepted 24.09.2026.