(Online) ISSN 2712-0554
Original Research

Heritage and Sustainable Development
Vol. 8, No. 2, 2026, pp.467-492
https://doi.org/10.37868/hsd.v7i1.2045

Public environmental expenditures and rural water quality: evidence from Kazakhstan

Raikhan Beisenova[1,3,4*], Aktoty Zhupysheva[1,2], Ayagoz Mashayeva[2], Balgyn Ashymova[5], Nurzhan Zholamanov[6]

[1] Department of Science, Kazakh National University of Sports, 010000, Karkaraly Hw, 15, Astana, Kazakhstan
[2] Department of State Audit, L.N.Gumilyov Eurasian National University, 010008, Satpayev str., 2, Astana, Kazakhstan
[3] Department of Science, Scientific Research Institute "Smart Eco-nnect", 010000, Tole bi str., 55, Astana, Kazakhstan
[4] School of Ecology, Yugra State University, Khanty Mansiysk, 628011, Chechov str., 16, Russia
[5] Department of Environmental management and engineering, L.N.Gumilyov Eurasian National University, 010008, Satpayev str., 2, Astana, Kazakhstan
[6] Department of Science, Kazakh National University of Water Management and Irrigation, 080000, Satbayev str, 28, Taraz, Kazakhstan

*Corresponding author E-mail: raikhan.beisenova@knus.edu.kz

Received Mar. 22, 2026
Revised Oct. 19, 2026
Accepted Oct. 28, 2026
Online Nov. 13, 2026

Abstract

This study is aimed to evaluate how public environmental expenditure relates to water quality in rural regions of Kazakhstan. It was held in Akmola and Zhambyl to compare regional disparities. The investigation process integrated regional investment data and hydrochemical indicators, such as total dissolved solids (TDS) and major ion composition. The novelty of this study lies in integrating long-term regional environmental expenditure data with hydrochemical indicators of rural drinking water quality to evaluate investment effectiveness under contrasting climatic and hydrogeological conditions in Kazakhstan. Methodology included statistical analysis, comparative regional assessment, and hydrochemical analysis of water. The geological conditions of the region were also taken into account when considering water quality outcomes. During the investigation, it was found that higher investments do not necessarily lead to improved water quality. The Zhambyl region showed relatively stable and optimal water quality despite the lower investment rates. Conversely, the Akmola region, despite attracting large amounts of investments, exhibited lower water quality. These regional disparities appear to be associated with differences in climatic and hydrogeological conditions rather than investment levels alone. In addition, areas with waterlogged soils showed elevated concentrations of TDS, indicating the significant influence of hydrogeological factors. Linear trend analysis demonstrated significant increases in environmental expenditure per capita in both regions (Akmola: slope = 3,439.95 tenge/person/year, R^2 = 0.626, p = 0.0064; Zhambyl: slope = 1,944.97 tenge/person/year, R^2 = 0.700, p = 0.0026), with both trends independently confirmed by the Mann–Kendall test ($p < 0.01$). Hydrochemical analysis revealed substantially higher and more variable TDS concentrations in Akmola, including values exceeding 5,000 mg/L in some localities, whereas most values in Zhambyl

This work is licensed under a Creative Commons Attribution License (https://creativecommons.org/licenses/by/4.0/) that allows others to share and adapt the material for any purpose (even commercially), in any medium with an acknowledgement of the work's authorship and initial publication in this journal.

ranged between approximately 200 and 400 mg/L. These findings indicate that higher environmental expenditure does not necessarily correspond to better rural water-quality outcomes because regional hydrogeological and climatic conditions may substantially influence the observed relationship. These findings support region-specific environmental investment policies that account for local hydrogeological, climatic, infrastructural, and institutional conditions when allocating public resources for rural water-quality improvement.

© The Author 2025.
Published by ARDA.

Keywords: Water quality, Environmental expenditure, Kazakhstan, Hydrochemistry, Rural areas

1. Introduction

1.1. Water security, rural water quality, and sustainable development

Methods for assessing SDG progress show that sustainable water management requires quantitative indicators and monitoring. Classifying indicators based on progress levels helps identify areas lagging behind in achieving progress and adjusting related policies. Significant progress in water reuse has been achieved thanks to technological advancements, including reverse osmosis technology. Furthermore, incorporating SDG water indicators into the water policy improves public expenditure effectiveness. Another benefit is the introduction of the social life cycle assessment (S-LCA) of water projects into sustainable development, which allows for taking into account the social impact of water projects on the population and development. In this context, the application of S-LCA of water projects helps in identifying solutions aimed at the sustainable development of the local system (for example, biogas technologies) [1]. Institutional factors determine the effectiveness of water policies in rural areas [2]. Public environmental spending is the major financing instrument for water supply and sanitation projects in transition economies.

Ensuring safe and high-quality access to drinking water remains a key challenge of sustainable development, especially for rural areas, where institutions, infrastructure and environmental protection are weaker than in urban areas. Thus, water quality cannot be seen merely as a technical, hydrochemical problem, but as a multi-dimensional factor in sustainable development that concerns public health and the ecological and socio-economic aspects of life. The concept of water security has evolved from a focus on water shortage to a multidimensional concept related to the economic, social, and governance aspects of water security. Gain, Giupponi and Wada [3] argue that water security includes not only the availability of water resources, but also the conditions of accessibility to and safe water, water quality, and management. It has been shown that even if the scarcity of water resources in the region is comparable, the results depend on the state of the infrastructure and the institutional environment, the significance of which for water quality outcomes is particularly apparent in rural regions, particularly in Kazakhstan, where the state of water quality depends not only on the natural conditions but also on the institutional efficiency of water governance and investment [3].

Another line of research emphasizes the need for integrated water management assessment based on the Sustainable Development Goals, with the greatest emphasis on the achievements of the sixth Goal (Clean Water and Sanitation). Garcia et al. [4] proposed a methodology for assessing SDG progress in urban water systems and analyzed trends, levels and thresholds by performance categories. This suggests that monitoring the progress of SDG 6 implementation and water policy effectiveness requires quantitative indicators. Although the authors focused on urban water systems, this logic is equally valid for rural areas where the effectiveness of the water policy also depends on environmental results and service quality [4]. Carden and Armitage [5] emphasize that the sustainability of water management is reflected in many indicators and cannot be assessed by considering only one or another of them. In the SIUWM framework, water resources, infrastructure, delivery services, environmental integrity and institutional capacity are brought under one analytical framework. This approach is also appropriate in studies on drinking water quality in rural areas where there can be no improvement in

water quality and water accessibility without considering conditions in infrastructure and services and their institutional management [5]. Romano and Akhmouch [6] also stress the governance-related conditions for achieving SDG-related outcomes: effective coordination of policies, stakeholder involvement and engagement, policy fit at the territorial level, institutional trust. The OECD's governance principles argue that even significant financial commitment may not yield results without well-coordinated water governance within and across sectors and jurisdictions. For Kazakhstan's rural areas, this indicates the need to frame public environmental spending not as a standalone line item, but rather within a wider governance framework which, in turn, may shape the effectiveness with which such investments improve water quality [6]. Recent optimization studies indicate that investment effectiveness depends not only on financial resources but also on appropriate water allocation strategies and adaptive management under water-scarce conditions [7]. Evidence from developing countries further demonstrates that investments in rural water infrastructure generate not only environmental but also broader socioeconomic benefits, although these effects vary substantially across regions [8].

1.2. Centralized, decentralized, and resilient water infrastructure

An important focus of recent water literature has been the debate over centralized, decentralized and hybrid solutions. Poustie et al. [9] point out that decentralized water supply and wastewater treatment measures could be lasting longer and be less harmful towards the environment compared to centralized measures. Their study was conducted in the context of low-density settlements, and they discovered that local practices, such as rain water harvesting and groundwater supply systems are the highest in resilience, and sanitation technologies, such as composting toilets, are environmentally safer than typical centralized wastewater management systems [9]. At the same time, highly-engineered systems, such as desalination, can prove to be more efficient and technically feasible but remain as a costly innovation. The understanding of technical feasibility and economic sustainability is an important factor for Kazakhstan, because the nation needs to strategically allocate funding to account for the realities of rural water systems [9].

Pot [10] further develops the question of resilience of water infrastructure, stressing the fact that investment into water infrastructure is mainly concerned with technical maintenance, when it should be concerned with long-term environmental uncertainty. He introduces such terms as absorptive, adaptive and transformational resilience capacities to emphasize on the more strategic dimension of the question. His work has a significant importance for Kazakhstan, where seasonal changes, outdated infrastructure and climate-induced water stress may render short term solutions ineffective [10].

Likewise, Wong, Rogers and Brown [11] frame water as a connector between the urban and rural planning, and the social processes, thus pushing the incentive of water sensitivity approach. Although their approach mainly focused on urban settings, the core message of their work, similarly to Pot's [10] ideas, is that momentary technical solutions to water quality may fail in the long-term without proper integration with water quality governance and community behavior. This work emphasizes that, in order for public expenses to improve in the water quality sector, they need to be a part of a wider socio-ecological change rather than an isolated occurrence [11].

1.3. Water footprint, circular economy, and pollution control

The concept of water footprint, as argued by Weerasooriya et al. [12], could be useful because it captures how water is used directly (in the case of the green and blue water footprints) for irrigation or consumption purposes, and indirectly (in the case of the gray water footprint) to dilute pollutants down to safe concentrations. In their paper, Weerasooriya et al. [12] show that industrial growth may have a strong influence on pollution load, and emphasize the need to reduce, reuse and recycle water alongside investment into cleaner treatment technologies [12].

Similarly to Weerasooriya et al. [12], Liang et al. [13] also consider the concept of ecological footprint but they adapt its methodologies to develop a three-dimensional water ecological footprint model. This model differentiates between the flow of renewable water resources and the consumption of long-term natural capital,

which may be beneficial for rural areas of Kazakhstan, where decline in water quality would benefit from recontextualization within the limits of overall sustainability rather than immediate water availability [13]. Additionally, Kakwani and Kalbar [14] stress that reduction, reuse and recycling of water should precede more costly downstream water management and restoration procedures. They argue that focusing on prevention and improved efficiency may have a more pronounced effect on water quality, compared to simply focusing on the end-of-pipe treatment [14].

Bosco et al. [15] propose a framework to assess water-smartness and water circularity through five dimensions: technical, environmental, economic, social and governance. It is important to consider this work because prior research in this area relied mainly on technical and economic performance. According to Bosco et al. [15], this earlier approach may render insufficient in the long-term because sustainability of solutions may be miscalculated due to such variables as environmental protection, financial viability, social acceptance, and alignment with governance frameworks being absent. In the Kazakhstani context, the framework may be especially relevant because it can help to minimize potential miscalculations in allocating public expenses to rural areas [15].

The significance of improving pollution control targeting is also pointed out by Zhang et al. [16], who find in a dynamic DEA that the low environmental efficiency of the water industry in China is not due to poor water consumption efficiency, but rather the poor quality of industrial wastewater treatment. This insight is very useful for rural drinking water studies, as the poor water quality in rural areas need not stem from a lack of physical water resources, but rather the poor treatment, pollution control, and environmental management of water resources, thus necessitating that public environmental expenditure be explored in relation to the entirety of the pollution control chain rather than just water distribution [16].

1.4. Public finance, investment efficiency, and prioritization

A fundamental block for literature in the topic is concerned with the financing of water infrastructures and how efficiently financial expenditures translate into outcomes. According to OECD [17], public spending continues to be the main mechanism for providing water and environmental infrastructures in many transition and developing countries, particularly when the incentive provided by the private sector cannot ensure adequate service to all, a fact that is highly relevant for rural Kazakhstan, where the main responsibility of improving water infrastructure and improving the environmental situation still lies with state interventions [17].

Despite this, the involvement of the private sector and the role of financial tools is expanding. Wang et al. [18] provide a comprehensive example of such financialization of water infrastructure in China, where public expenditure has been prolongedly insufficient. They describe how financial tools could be utilized to raise funds and improve such a long-standing issue. They also note that the financial regime is tied to policy frameworks and public accountability, thus the amount of public investment does not guarantee results unless the institutional governance structures effectively manage those funds [18].

Reis, Vargas Magaña and Vélez Villegas [19] raise a comparable cautionary note in their more critical discussion of financialization. They argue that increasing the role of the market may lead to an aggravation of socio-spatial inequality if capital flows to more profitable areas. Rural localities represent exactly this situation where, if water investment becomes overly market-oriented, poorer and isolated populations might get neglected, which further justifies concentrating on public environmental expenditure to reduce regional differences in water quality [19].

According to Green et al. [20], on the other hand, a broader perspective should be taken in the water financing debate, suggesting that private investment is compatible with the attainment of water security and resilience if it is supported by regulation, information systems, and public policies. The results of this study show that nature-based solutions, digitalization, and the modernization of infrastructure all represent forms of financial mobilization that are not by themselves sufficient, as what is needed is an adequate regulatory and informational framework to ensure that investment promotes sustainability [20].

Macchiaroli, Dolores and De Mare [21] directly discuss the question of the prioritization of expenditure. Employing the Analytic Hierarchy Process, they demonstrate that the prioritization of water infrastructure investments should be conducted considering social criteria, cost of investment, operational burdens, and impacts on the environment. The application of their method to a wastewater treatment plant case in Italy showed that such plant is usually considered a priority, regardless of whether decision-makers have conflicting interests. The Italian example is relevant to Kazakhstan, where public expenditure on environmental protection is made under budget constraints, and thus water quality in rural areas depends not just on the increase of environmental expenditure, but on its optimal prioritization [21].

Stoyanova [22] reinforces the idea that it is important to look beyond the total public expenditure on environmental protection to assess the effectiveness of financing. In the case of Bulgaria, she shows that, although the implementation of European funds led to an increase of access to water and sanitation, the impact was different between regions because the regions were more effective at transforming the public environmental expenditures into investment projects. For your article, this is an additional support for the thesis of public environmental expenditure efficiency assessment in the regional terms and not just in the financial [22].

The study demonstrates that financial compensation mechanisms improve water quality only when combined with effective watershed management, while climatic conditions and legacy pollution continue to influence environmental outcomes [23]. Recent studies increasingly distinguish between the amount of environmental expenditure and its effectiveness. While larger public investments generally improve environmental infrastructure, empirical evidence suggests that financial inputs alone rarely guarantee better environmental outcomes. The effectiveness of environmental expenditure depends on governance quality, institutional capacity, investment prioritization, and regional environmental conditions. Consequently, evaluating environmental expenditure requires not only measuring investment volumes but also assessing whether these investments translate into measurable improvements in environmental quality [20].

Finally, Zhong et al. [24] argue for considering the effects of public expenditure on water on welfare as well as on economic efficiency. They have used a general equilibrium model to analyze how water infrastructure investment affected different socioeconomic groups, including industries, landowners and households with different levels of income. Their analysis showed that expanding the infrastructure may seem economically justified long-term but the burden of financing might fall unevenly across different layers of population. This may have different implications for rural localities in Kazakhstan, where poorer households may be facing higher costs from the adaptation to poor water quality [24].

1.5. Performance measurement, benchmarking, and regional heterogeneity

In another area, lo Storto [25] studies efficiency in the water sector and shows that, while water service efficiency is generally considered an important indicator in the evaluation of water utilities, significant regional variations were found due to water infrastructure deficits and the inefficiencies and technology of scale. The Italian case revealed by the meta-frontier efficiency analysis was that regions in the south were clearly lagging behind those in the north and central, which was attributed to the different levels of investment, as well as different economic and environmental operating conditions. For your study, this finding is relevant because it implies that the relationship between public environmental expenditures and water quality in different regions of Kazakhstan may differ depending on whether the water infrastructure is in good condition, its size and capacity and the political and economic context [25].

The dynamic benchmark approach of Molinos-Senante and Maziotis [26] allows researchers to evaluate water sustainability performance continuously over time and distinguish internal performance improvement from external changes within the sector. This is especially helpful for your paper because it suggests that your analysis of expenditures and water quality in rural areas should ideally be done in a dynamic manner and that improvement may be due to a learning and adaptation process by the institutions responsible, not because of a certain amount of investments in a certain year [26].

Sakai [27] provides a systematic review on performance measurement of water utilities, revealing problems such as excessive focus on mathematical optimization, low data quality, low connection between academic research and practical decision-making and a lack of attention to environmental and social considerations. Your study design might need to be informed by these problems to ensure that performance metrics are robust and that their use in evaluating the water sector is not overly reductionist [27]. Similarly, Wendling et al. [28] find that most current assessment systems do not match the coverage of all SDG indicators to the necessary extent, which is problematic, among other things, in terms of ensuring sanitation, housing and disaster risk reduction and response. This strengthens your argument that water policy is still evaluated by separate indicators. More integrated assessment frameworks would be needed to fully cover water-related indicators, and chemical measurements in rural water quality should therefore be combined with sustainability assessment, governance and infrastructure aspects in the context of your paper [28].

1.6. Social and institutional dimensions

The literature on infrastructure and environmental spending also recognizes its impact on social aspects. Benoît et al [1] created the methodological foundations of Social Life Cycle Assessment, and the method identifies social hotspots and evaluates effects on different stakeholders, beyond the conventional environmental metrics in the field. While the method was not originally designed for rural drinking water systems, it is highly relevant for understanding the role of the sector in rural communities [1]. Osorio, Cobo and Sanchez [29] apply the S-LCA framework to assess energy and social vulnerability in rural communities. Their case study of Colombia demonstrates that decentralized approaches to rural water supply can help improve infrastructure and social resilience of rural communities when aligned with broader development objectives based on principles of justice and equity, providing new opportunities for the study of the water quality and environmental spending relationship in Kazakhstan [29]. In their work, Kennedy, Zhong and Corfee-Morlot [30] consider environmental infrastructure in the context of a wider green transition, and advocate for large investments into water infrastructure, pollution control and industrialization as means to maintain long-term ecological equilibrium. Chen et al. [31] also highlight that the accountability system alongside environmental monitoring and assessment systems will ensure the integration of natural resource protection into government performance. Collectively, these two works argue that public environmental investments are the most effective when situated within a broader system of responsibility, oversight, and ecological stewardship [31].

1.7. Kazakhstan context and research gap

Recent empirical studies in Kazakhstan confirm that water quality in rural regions can differ drastically from settlement to settlement, as it is highly dependent on supply source, hydrochemical profile, and microbiological conditions. In their research on water quality in villages across Pavlodar and Akmola, Beisenova et al. [32] note that, despite the fact that, in a number of villages, concentrations of anions and cations exceeded maximum allowed concentration, residents expressed relative satisfaction with water quality primarily due to a trusted supply source. Several empirical indicators were then compared to perceived water quality, which resulted in mineralization being associated with water hardness, while microbiological contamination – with poor taste, bad odor or high salinity. These findings are particularly important because they highlight the role of socio-economic and cultural factors in how water quality is perceived in rural regions [32]. Hydrochemical and hydrobiological parameters also contribute to overall ecological assessment of water in Kazakhstan. In their study of the phytoplankton and saprobity of Lake Maybalyk, Tekebayeva et al. [33] observed the diversity of phytoplankton, saprobity indicators and hydrochemical properties, which allowed them to define, with minimal deviation, Lake Maybalyk as a member Class III in terms of water quality. Biomonitoring using microalgae and other water organisms was shown to be a useful complement to traditional chemical assessment methods, enabling an understanding of the ecosystem's self-purification capacity. While this study was carried out in a lake environment and does not directly study rural drinking water systems, this article is highly relevant to the subject of the paper, as it emphasizes the need for ongoing monitoring and ecological assessment in order to promote sustainable resource management of Kazakhstan's water resources [33].

The review of the literature has shown that water quality outcomes are contingent on infrastructure design, pollution control measures, quality of governance, financing arrangements and regional variation. The reviewed papers have made important contributions, showing that water security depends upon institutional and socio-economic settings, that in some situations decentralized and robust systems are more effective than mainstream approaches, that there is a focus on the circular economy concept and wastewater treatment, and that the efficacy of public and joint investments is conditioned by the quality of governance and spatial congruence.

Despite the growing literature on water governance, environmental expenditure, infrastructure performance, and sustainable water management, an important empirical gap remains. First, previous studies have predominantly focused on urban water systems, water utilities, and industrial water management, whereas empirical evidence on rural drinking water quality remains comparatively limited. Second, existing studies commonly examine environmental financing, infrastructure performance, or hydrochemical water quality separately, while relatively few studies directly link public environmental expenditure to measured hydrochemical outcomes. Third, empirical evidence from Central Asia remains scarce, particularly regarding whether differences in public environmental expenditure are associated with different rural water quality outcomes under contrasting climatic and hydrogeological conditions. This gap is particularly relevant for Kazakhstan, where substantial regional differences in climate, hydrogeology, settlement structure, and environmental expenditure may influence the effectiveness with which public financial resources are translated into measurable environmental outcomes. This study addresses these gaps by integrating long-term regional environmental expenditure data with field-based hydrochemical indicators of rural drinking water quality in two environmentally contrasting regions of Kazakhstan.

Accordingly, the primary aim of this study is to assess the relationship between public environmental expenditure and rural drinking water quality while accounting for regional climatic and hydrogeological heterogeneity. Specifically, the study examines whether differences in regional environmental expenditure are associated with differences in measured hydrochemical characteristics of rural drinking water in the Akmola and Zhambyl regions of Kazakhstan.

The study addresses the following research questions: Is regional public environmental expenditure associated with rural drinking water quality?

Do the observed relationships between environmental expenditure and hydrochemical water quality indicators differ between the Akmola and Zhambyl regions?

To what extent can regional climatic and hydrogeological heterogeneity help explain differences in the apparent effectiveness of environmental expenditure?

1.8. Research novelty

The novelty of this study lies in the integrated assessment of public environmental expenditures and rural drinking water quality within a single analytical framework. Unlike previous studies, which primarily examined environmental financing, water governance, or hydrochemical characteristics separately, this research combines long-term regional investment statistics (2015–2024) with hydrochemical indicators of drinking water quality collected from rural settlements in two climatically contrasting regions of Kazakhstan. Furthermore, the study explicitly considers the role of regional hydrogeological and climatic heterogeneity in explaining differences in investment effectiveness. By integrating financial, hydrochemical, and territorial dimensions within a single comparative framework, this study provides new empirical evidence from Central Asia and contributes to understanding why higher public environmental expenditure does not necessarily translate into proportionally better rural water quality outcomes under heterogeneous regional conditions.

2. Research method

Regional data was collected from Akmola and Zhambyl, which encompassed per capita ecological spending for each region from 2015 to 2024. Dissolved oxygen and dissolved solids concentrations were measured for the

year 2024 for both Akmola and Zhambyl (Figure 1), then the intensity of the regional environmental investment was compared with regional water quality to evaluate whether there is an alignment between them. Figure 1 illustrates a conceptual framework of how regional environmental investment interacts with water quality in a given village. While environmental expenses cover governance and infrastructure, which influence regional-level indicators, such as hydrogeology and management efficiency, which then impact the quality of water.

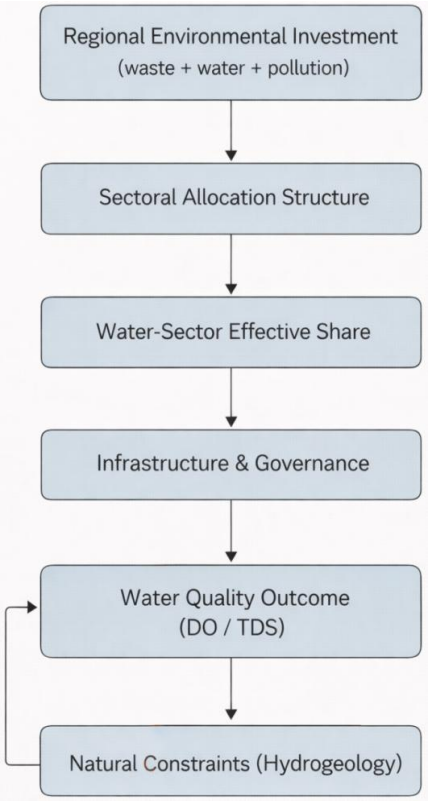


Figure 1. Conceptual framework of the Investment–Water Quality Interaction Model

Note: DO – dissolved solution; TDS – total dissolved solids

The conceptual model represents the multi-layered interaction between regional environmental investments and village-level water quality outcomes. Investments do not impact the water quality directly, they do, however, contribute to governance and infrastructure, but the ultimate impact on water quality indicators is made by hydrological controls and management efficiency. The variables used in this study, together with their operational definitions, units of measurement, data sources, and observation periods, are summarized in Table 1.

Table 1. Definitions, data sources, and measurement units of the study variables

Variable	Definition	Unit	Source	Period
Environmental expenditure	Public environmental expenditure per capita allocated by regional authorities	tenge/ person	Bureau of National Statistics of Kazakhstan	2015–2024
Population	Annual regional population	persons	Bureau of National Statistics of Kazakhstan	2015–2024
Total dissolved solids (TDS)	Sum of dissolved inorganic ions calculated from hydrochemical composition	mg/L	Field hydrochemical measurements	2024
Dissolved oxygen (DO)	Oxygen saturation in drinking water samples	%	Field measurements	2024
Major ions	Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^{-}, SO_4^{2-}, Cl^{-}	mg/L	Laboratory hydrochemical analysis	2024

Linear trend analysis was selected because the objective was to evaluate long-term changes in regional environmental investments rather than estimate causal panel effects. Since hydrochemical observations were available only for single sampling period (2024), panel-data estimators such as fixed-effects or random-effects models were not appropriate. To ensure transparency and reproducibility, all study variables were operationally defined prior to statistical analysis. Environmental expenditure and population data were obtained from official regional statistics for the period 2015–2024, whereas hydrochemical indicators were measured during field sampling conducted in 2024. These variables were selected to evaluate the relationship between regional environmental investments and rural drinking water quality under contrasting climatic and hydrogeological conditions.

The linear regression analysis was used exclusively to characterize the direction and magnitude of temporal investment trends and was not intended as a causal or predictive econometric model. Because time was the only explanatory variable, multicollinearity was not applicable. Given the short annual series (n = 10), the linear regression results were interpreted descriptively rather than as a causal econometric model. To reduce dependence on parametric assumptions regarding residual distribution, variance structure, and temporal dependence, the linear trend results were independently evaluated using the non-parametric Mann–Kendall test and Sen's slope estimator. Consequently, multicollinearity diagnostics were not relevant because time was the only explanatory variable. Given the short annual time series (2015–2024), regression results were interpreted descriptively and were complemented by non-parametric and comparative analyses to assess the robustness of the main findings.

2.1. Research area

The Akmola Region is one of the northern regions of Kazakhstan, and it borders Kostanay on the West, North Kazakhstan on the North, Pavlodar on the East, and Karaganda on the South. The area of the region is approximately 146,200 km2, which is 5,4 % of the total territory of Kazakhstan; its population stands at 787,300 as of January 1, 2025, with a rural population of around 336,900 people. Administratively, the region includes the capital of Kazakhstan (Astana), as well as three cities of regional importance (Kokshetau, Stepnogorsk, and Koshhy), several small urban settlements, and nearly 600 rural settlements.

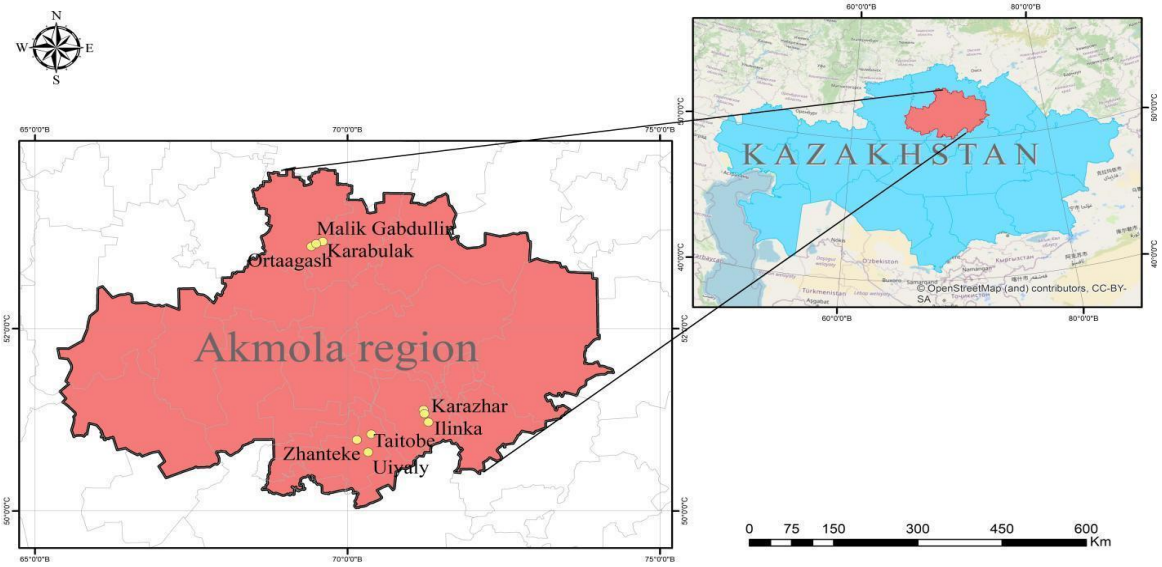


Figure 2. Research the Akmola region area of Kazakhstan [35]

Note: yellow rounds are 9 sample villages: Malik Gabdullin, Karabulak, Ortaagash are in Zerendy district, Ilyinka, Karazhar, Taitobe are in Tselinograd district and Znanteke, Karaegin, Uiyaly are in Korgalzhyn district

The natural resources of the region are characterized by forest and water reserves, which comprise 514,800 and 200,800 hectares respectively, agricultural land resources, which comprise 14.6 million hectares of land, 10.9 million of which is dedicated to agricultural purposes. The economy of the region is heavily engaged with

agricultural activity and industry, thus putting considerable strain on natural resources of the area [34]. This profile makes Akmola an exemplary candidate to investigate the correlation between environmental investments and water quality change in rural areas (Figure 2). In Akmola region, 3 rural districts and 9 rural settlements were randomly selected from diverse landscapes. Malik Gabdullin, Karabulak, and Ortaagash are in Zerendy district, while Ilyinka, Karazhar, and Taitobe are in Tselinograd district, and Znanteke, Karaegin, and Uiyaly are in Korgalzhyn district. Zerendy district is primarily covered by forests, Tselinograd district consists mostly of steppes, and Korgalzhyn district is largely a wetland. Because rural settlements are so prevalent and most communities here rely on decentralized water supplies, this area is ideal for research investigating how environmental spending influences water quality's hydrochemical indices.

Zhambyl region is situated in southern Kazakhstan, with a total land area of about 144,300 sq. km. It is bounded by Almaty region in the east, Turkestan region in the west, Karaganda region in the north and the Kyrgyz Republic in the south. Because of its geographical position and climate, Zhambyl region is an important area for water resource management and studying environmental conditions in southern Kazakhstan. With the population of about 1.2 million (as of 1 January 2025), it can be noted that a substantial proportion of the region's population lives in rural settlements. The region consists of the regional center of Taraz, regional cities, rural district settlements and a large number of small settlements scattered by regions. The relatively high share of the rural population and the large number of agricultural villages make the region of significant relevance for research of water supply and water quality issues in rural areas (Figure 3).

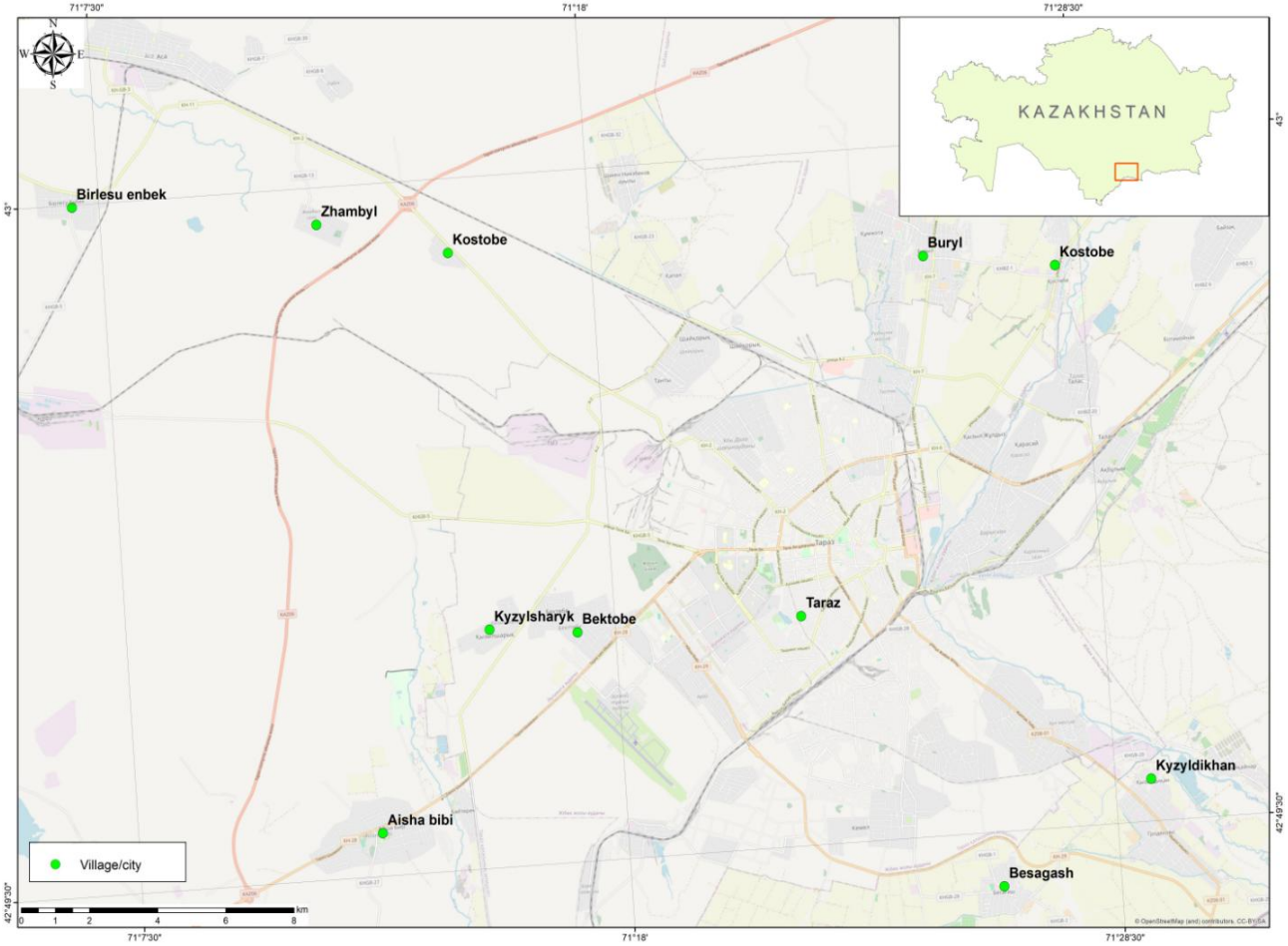


Figure 3. Research the Zhambyl region area of Kazakhstan

Note: yellow rounds are 11 sample villages: Kyzyldikhan, Besagash from Zhas orken district, Kosstobe1, Zhambyl, Birlesu enbek, Bektobe, Aisha bibi, Kyzylsharyk from Zhambyl district, Kosstobe2, Buryl from Baizak district and the private sector of Taraz city

The main areas of Zhambyl region economy are agriculture, industry and mining. Agricultural production, including crop and livestock production, play a significant role for regional economy and affects the use of land

and water resources. For this reason, irrigation and local water supply systems are a key element of rural life and environmental sustainability [36]. The specific natural condition and economic activity of this region impose different pressures on the water resources. Many rural settlements are supplied water from decentralized water supply, in some cases, via wells and boreholes, which may result in exposure of drinking water sources to environmental pollution and hydrochemical indicators changes, and consequently, dissolved oxygen is a relevant index to determine the environmental status of water and its usability. Taking into account the above, the case of Zhambyl region seems to be a convenient object to analyze the connection between the state environmental expenditures and hydrochemical indices of drinking water quality in rural areas. The presence of the agricultural areas, rural settlements with drinking water supply by decentralized sources and the existing program of state investments in environmental area in this region allow for comparative analysis of the relationship between expenditures and hydrochemical indices. For the aim of the research 11 sample villages are randomly selected from 3 districts. Kyzyldikhan, Besagash from Zhas orken district, Kosstobe1, Zhambyl, Birlesu enbek, Bektobe, Aisha bibi, Kyzylsharyk from Zhambyl district, Kosstobe2, Buryl from Baizak district and the private sector of Taraz city.

2.2. Drinking water sources and rural Akmola and Zhambyl area

Drinking water sources were identified from the research sample Akmola and Zhambyl regions' rural area. The rural area is 20 random villages: in Akmola region - Malik Gabdullin, Karabulak, Ortaagash are in Zerendy district, Ilyinka, Karazhar, Taitobe are in Tselinograd district and Znanteke, Karaegin, Uiyaly are in Korgalzhyn district; in Zhambyl region - Kyzyldikhan, Besagash from Zhas orken district, Kosstobe1, Zhambyl, Birlesu enbek, Bektobe, Aisha bibi, Kyzylsharyk from Zhambyl district, Kosstobe2, Buryl from Baizak district and the private sector of Taraz city (Table 2).

Table 2. Geolocation of the drinking water sample villages of research areas

Region	District	Village	x	y
Zhambyl	Zhas orken	Kyzyldikhan	71°29′05″E	42°50′15″ N
Zhambyl	Zhas orken	Besagash	71°25′42″ E	42°48′57″ N
Zhambyl	Zhambyl	Kosstobe1	71°15′13″ E	42°58′40″ N
Zhambyl	Zhambyl	Zhambyl	71°11′58″ E	42°59′27″ N
Zhambyl	Zhambyl	Birlesu enbek	71°07′00″ E	43°00′01″ N
Zhambyl	Zhambyl	Bektobe	71°23′14″ E	43°00′06″ N
Zhambyl	Zhambyl	Aisha bibi	71°17′36″ E	42°51′25″ N
Zhambyl	Zhambyl	Kyzylsharyk	71°15′33″ E	42°53′12″ N
Zhambyl	Baizak	Kosstobe2	71°27′50″ E	42°57′26″ N
Zhambyl	Baizak	Buryl	71°25′41″ E	42°58′06″ N
Akmola	Zerendy	Ortaagash	69°25′23″ E	52°52′21″ N
Akmola	Zerendy	Karabulak	69°36′13″ E	52°55′30″ N
Akmola	Zerendy	Malik Gabdullin	69°29′55″ E	52°54′09″ N
Akmola	Korgalzhyn	Uiyaly	70°19′50″ E	50°39′09″ N
Akmola	Korgalzhyn	Zhanteke	70°09′20″ E	50°47′20″ N
Akmola	Korgalzhyn	Karaegyn	70°22′51″ E	50°51′03″ N
Akmola	Tselinograd	Iliyinka	70°12′59″ E	51°07′06″ N
Akmola	Tselinograd	Karazhar	71°13′47″ E	51°04′10″ N
Akmola	Tselinograd	Taitobe	71°17′48″ E	50°59′05″ N

2.3. Data Sources, quality control and limitations

The data were sourced from the open sources of Kazhydromet and the Bureau of Statistics, specifically the long-term collection from the regional statistical database covering 2015-2024 [37], [38]. Several constraints must be recognized regarding this study. Specifically, the study is limited by the mismatch in spatial between quality and investment data, the single-year quality observation, and the absence of village-level data on the water sector investments. As the study covers only two regions, it is difficult to draw broad conclusions; furthermore, only the current quality characteristics are examined, which means that the effect of investments might be postponed in time. Future works need to use panel data combining water quality in different years with investment in water infrastructure. In addition, the observational design is potentially affected by endogeneity in public expenditure allocation, because regions with poorer baseline environmental or infrastructure conditions may receive greater investment. Therefore, the observed relationship between expenditure and water quality should not be interpreted causally.

2.4. Analysis of hydrochemical components

Hydrochemical analysis of surface and groundwater, aimed at determining water type, identifying geochemical processes, and assessing suitability for various purposes, was based on the study of key cations and anions. Concentrations of major cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and anions (HCO_3^-, SO_4^{2-}, Cl^-) were used to determine the total dissolved solids (TDS) in samples. To verify the analytical accuracy of chemical data in drinking water, ion balance calculations were performed. TDS was calculated as the sum of concentrations of dominant cations and anions detected in water samples [39]. TDS was computed according to equation (1):

$$\mathrm{TDS} = \sum_{i=1}^{n} \mathrm{Ci} \quad (1)$$

where: Ci – concentration of dissolved ions.

TDS values were derived from electrical conductivity (EC) data using an empirical conversion factor of 0.64, a standard approach for natural freshwater systems. This method is grounded in the third and final edition of a foundational work that established key principles for understanding freshwater chemistry and hydrogeochemical processes in geology, hydrology, and ecology [39]. TDS calculations from EC followed equation (2).

$$\mathrm{TDS} = \mathrm{k} \times \mathrm{EC} \quad (2)$$

where: TDS – total dissolved solution; EC – electroconductivity; k – conversion factor.

The Piper diagram was used to graphically display the chemical composition of water samples, as it is a widely used tool in environmental and ecotoxicological studies [40], [41]. The most typical cations for this diagram are two alkaline earth metal ions: Ca^{2+} and Mg^{2+} and one alkali metal ion: Na^{+} [42]. The typical anions include one weakly acidic ion: HCO_3^- and two strongly acidic ions: SO_4^{2-} and Cl^-. Piper proposed this diagram based on the assumption that ions in water are generally in a state of chemical equilibrium [43], [44].

2.5. Statistical and correlation analysis

Investment dynamics in environmental aspects were investigated considering temporal and spatial characteristics. Trend analysis showed short periods of fluctuations as well as periods of long-term stabilization, which might be related to population growth. Statistical data for each water quality indicator are presented as mean values plus standard error (SE). The Piper diagram displays mean concentrations of key ions: potassium (K), sodium (Na), bicarbonates (HCO_3^-), chlorides (Cl^-), and sulfates (SO_4^{2-}) which are alongside their comparison with maximum permissible concentrations (MPCs). Statistical data processing was performed using Python version 3.12. This approach is widely applied in diverse studies, including field-based environmental research [45], as well as in analyses of environmental and economic criteria for the efficient use of natural resources, considering interrelationships among indicators identified through correlation analysis [46]. The selection of statistical methods was determined by the structure of the available dataset and the objectives of the

study. Long-term regional investment statistics (2015–2024) were analyzed using descriptive statistics and linear trend analysis to evaluate temporal changes in environmental expenditures. Hydrochemical indicators were obtained from field measurements conducted during a single sampling campaign in 2024; therefore, panel-data estimators such as fixed-effects or random-effects models were not appropriate because repeated observations of water quality over time were unavailable. Instead, comparative statistical analysis, Spearman correlation, Kruskal–Wallis and Dunn's post hoc tests, together with hydrochemical interpretation using Piper diagrams, were applied to evaluate regional differences and relationships between environmental expenditures and water quality indicators.

2.5.1. Robustness and sensitivity analysis

To assess the robustness of the obtained results, several complementary analytical approaches were applied. Long-term investment trends were evaluated using linear trend analysis, whereas regional differences in hydrochemical indicators were examined using non-parametric statistical methods (Kruskal–Wallis test followed by Dunn's post hoc test). In addition, Spearman's rank correlation analysis was performed to assess monotonic relationships among the investigated variables without assuming normal data distribution. The consistency of the findings obtained from statistical analyses was further verified through hydrochemical interpretation using Piper diagrams and comparative analysis of TDS and dissolved oxygen distributions. The agreement among these independent analytical approaches supports the robustness of the reported regional patterns and reduces the likelihood that the observed relationships are attributable to a single analytical technique. To assess the robustness of temporal changes in environmental expenditure, linear trend analysis was complemented by the non-parametric Mann–Kendall test and Sen's slope estimator. The Mann–Kendall test was used to determine the direction and statistical significance of monotonic trends in annual environmental expenditure per capita over 2015–2024, while Sen's slope estimator was applied to quantify the magnitude of annual change. This complementary approach was particularly appropriate given the relatively short annual time series and provided a robustness check that was less sensitive to outliers and distributional assumptions than linear regression alone.

3. Results and discussion

3.1. Results

3.1.1. Investment dynamics

The average investment per capita per year in the Akmola and Zhambyl regions over the period of 2015-2024 were different, yet the investment trends of the regions over the past years are similar. The fluctuations in the total amount of investments are not large. The average annual investment per capita over the period of 2015-2024 are shown in Figures 4 and 5. Figure 4 presents the average annual investments, population growth, and other parameters of both regions in 2015-2024 [37]. The dynamics of environmental investments, population, and other parameters of both regions in 2015-2024 are shown in Figures 4 and 5.

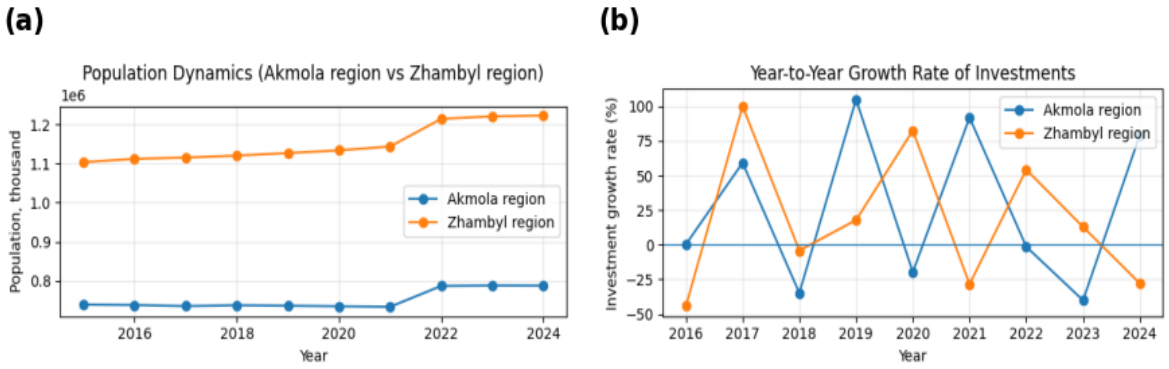


Figure 4 (a0 and (b). Investment dynamics of the Zhambyl and Akmola region in Kazakhstan

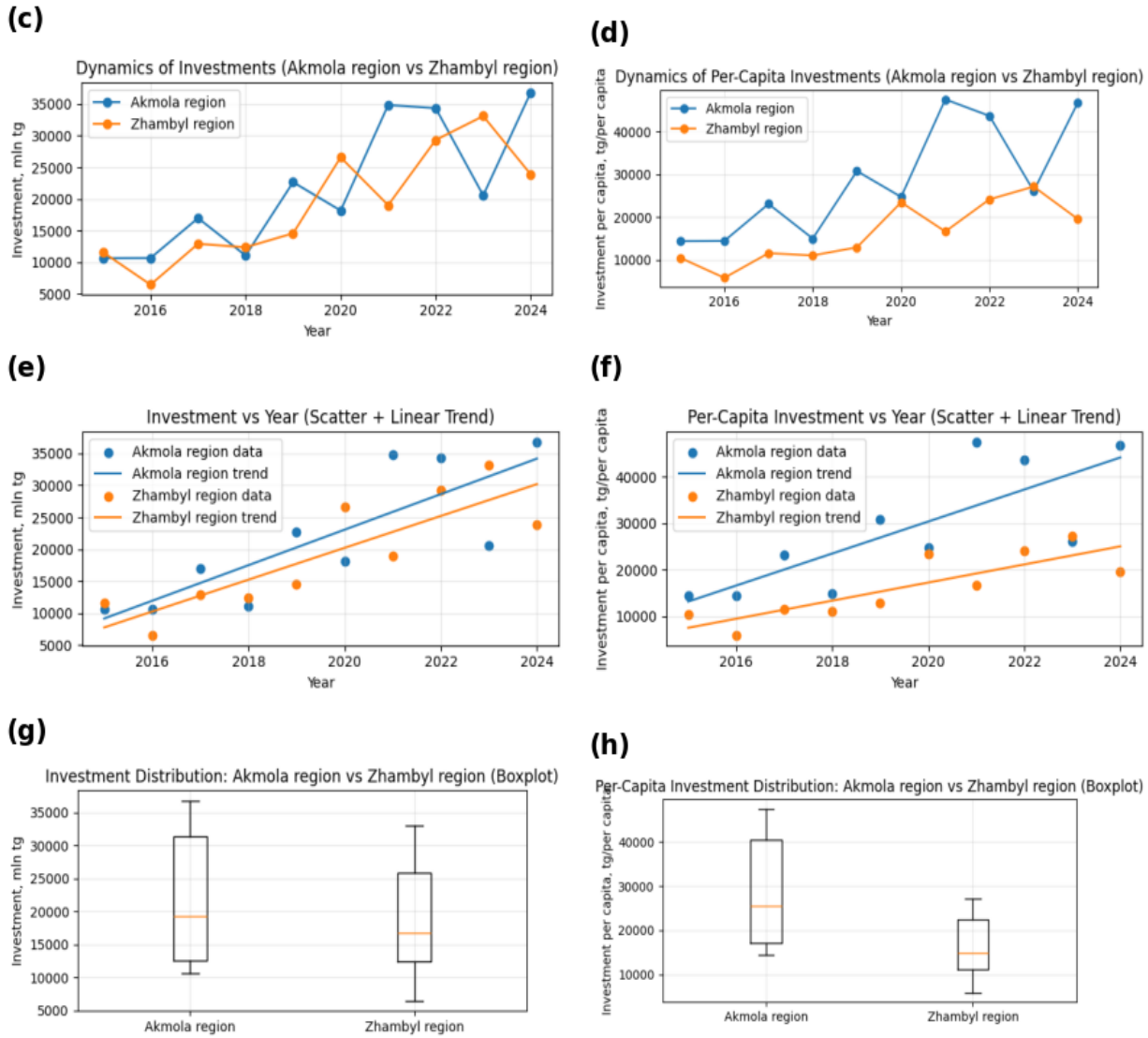


Figure 4. Investment dynamics of the Zhambyl and Akmola region in Kazakhstan

Figure 4a indicates that both regions have a relatively stable population. The population in the Zhambyl region is larger than that in the Akmola region. The population change in the Akmola region is smaller in 2015-2024. The growth rate of the amount of investment in environmental protection in both regions is quite different and shows different fluctuation characteristics (Fig. 4b). Both regions alternate years of increasing and decreasing investment amounts, possibly due to the influence of the annual budget and annual program for funding environmental projects. However, environmental investment in the Akmola region has more years of rapid growth, particularly since 2019, while in the Zhambyl region, the investment trends are more balanced. Figure 4c shows that the volume of investments in environmental protection in the region is increasing. From 2015 to 2024, Akmola spent more money on environmental protection. Since 2020, Akmola's spending increased a lot. The investment of environmental protection projects in the Zhambyl region also increased, but less than in the Akmola region. According to Figure 4d, the average annual investment per capita in the Akmola region is higher than the average investment per capita in the Zhambyl region, which may mean that the Akmola regional budget allocated more money for the environment. Figures 4e, f illustrate a positive linear trend between the average amount of investments in environmental protection of the Akmola region and the time; the same is true for the Zhambyl region. The amount of investments in the Akmola region has fluctuated, and there is a positive trend for the growth of the Akmola region investments. The Akmola region's investments grow at a faster rate than the Zhambyl region.

Figures 4g–h further illustrate the structural disparities between the two regions. The boxplots, representing investment allocation, show broader distribution range and greater median levels for the Akmola region, while the Zhambyl region appears to be more constrict with lower median levels.

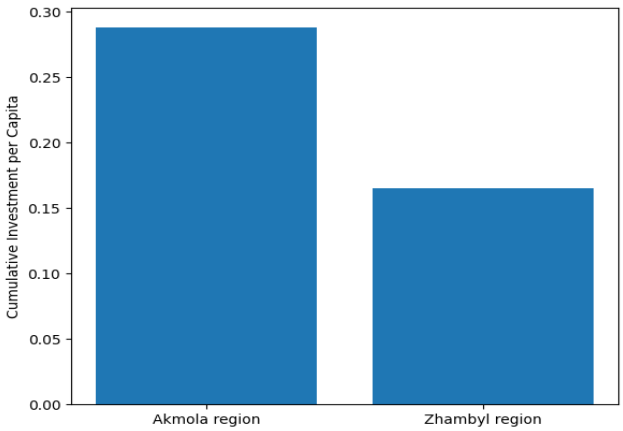


Figure 5. Cumulative investment per capita in the Zhambyl and Akmola region of Kazakhstan

Figure 5 depicts cumulative environmental investment per capita for each region. According to the diagram, The Akmola region is evidently higher in overall amount of environmental investment compared to Zhambyl, reflecting stronger financial support for environmental initiatives and sustainability of long-term development of ecological infrastructure.

The statistical trend analysis confirmed a significant increase in environmental expenditure per capita in both regions over 2015–2024. In Akmola, linear regression indicated an average increase of 3,439.95 tenge per person per year ($R^2 = 0.626$, $p = 0.0064$). The non-parametric Mann–Kendall test independently confirmed a significant increasing trend ($\tau = 0.689$, $Z = 2.683$, $p = 0.0073$), while Sen's slope indicated a median annual increase of 3,841.27 tenge per person. In Zhambyl, environmental expenditure per capita increased by an average of 1,944.97 tenge per person per year according to the linear model ($R^2 = 0.700$, $p = 0.0026$). This trend was likewise confirmed by the Mann–Kendall test ($\tau = 0.733$, $Z = 2.862$, $p = 0.0042$), with a Sen's slope of 1,893.91 tenge per person per year. Thus, both parametric and non-parametric approaches consistently demonstrate statistically significant increases in environmental expenditure in both regions, while the magnitude of the increase was substantially greater in Akmola (Table 3).

Table 3. Trend analysis of environmental expenditure per capita in Akmola and Zhambyl regions, 2015–2024

Region	Linear slope, tenge/person/ year	R^2	Linear p	MK Z	Kendall τ	MK p	Sen's slope, tenge/person/ year	Trend
Akmola	3,439.95	0.626	0.0064	2.683	0.689	0.0073	3,841.27	Significant increase
Zhambyl	1,944.97	0.700	0.0026	2.862	0.733	0.0042	1,893.91	Significant increase

3.1.2. Village-level water quality variability

The data on dissolved oxygen (DO) in the villages of the Zhambyl region exhibit a great degree of irregularity, where levels of dissolved oxygen saturation differ across various local water bodies. DO levels also showed significant variation among villages (Figure 6). The highest median DO was observed in the districts of Aisha Bibi and Bektobe (68–72%), lower median value was found in Buryl, Taraz and Besagash (35–42%), indicating lower concentrations of oxygen. At the same time, Kosstobe-2 demonstrated a significant spread, which may be due to high variance within the village. Some villages had outliers, which suggests periodic jumps in oxygen saturation levels. These distributions support the existence of marked DO variability throughout the study area.

Villages in the Zhambyl region showed substantial variability in their DO levels (Kruskal-Wallis test H = 24.46, p = 0.006) (Figure 7). Dunn's test with Bonferroni correction were applied for post-hoc paired comparison, and did not reveal any statistically significant differences between specific pairs of villages. Spearman's correlation analysis also did not reveal any significant relationship between DO and electrical conductivity (ρ = 0.06, p = 0.67). Moreover, linear regression confirmed the lack of explanatory power (R2 = 0.001), thus mineralization also does not significantly affect oxygen saturation in this region.

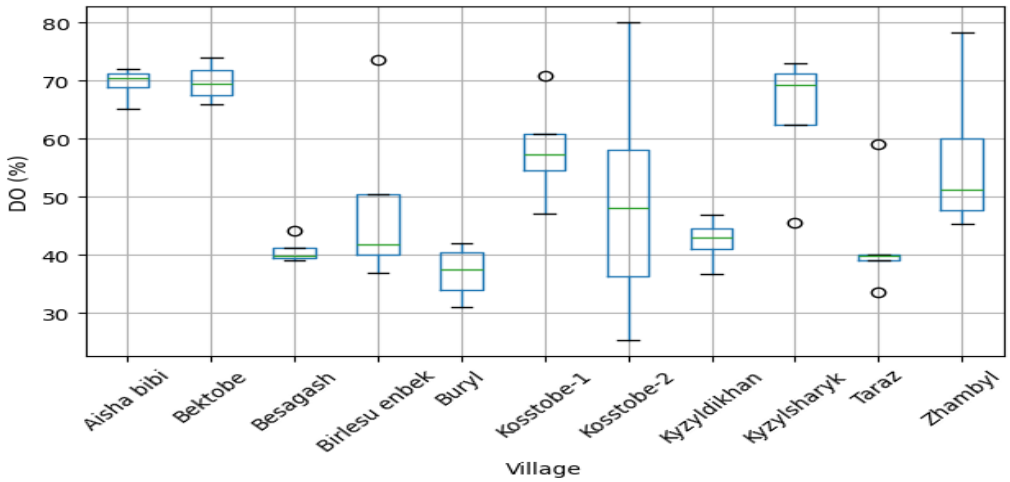


Figure 6. Boxplot of spatial variation of dissolved oxygen (DO, %) across villages of Zhambyl region

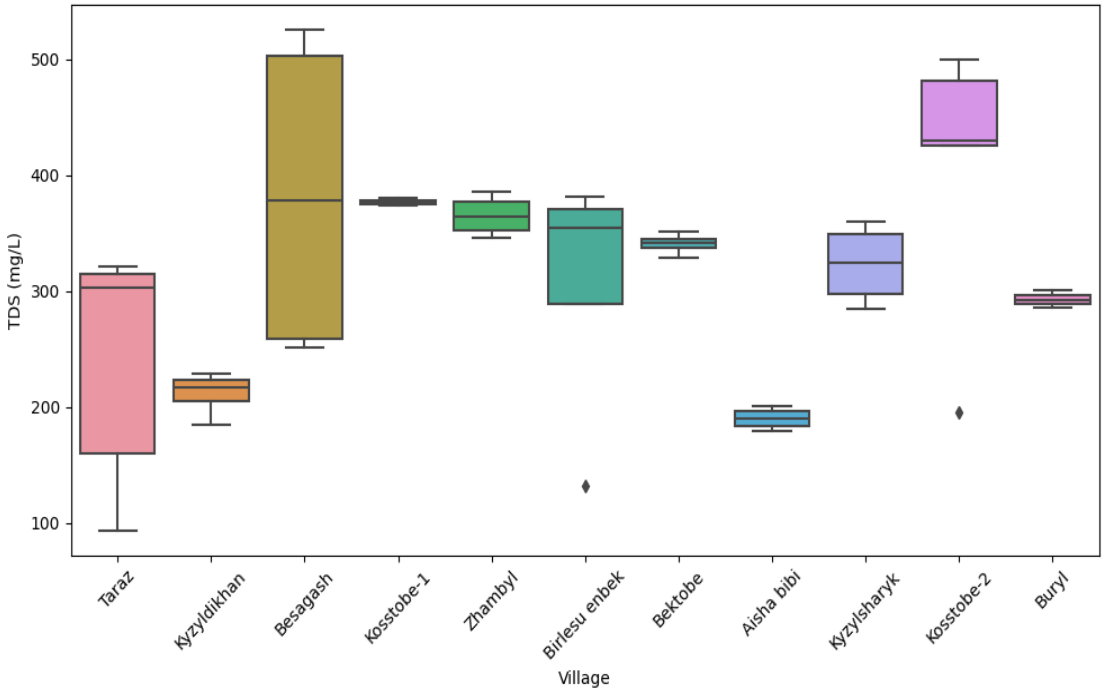


Figure 7. Boxplot of spatial variation of total dissolved solids (TDS, mg/L) across villages of Zhambyl region

According to Piper diagram, the hydrochemical composition of nine villages in Akmola region is dominated by carbonate weathering processes, reflecting in a clustering of samples within Ca–Mg–HCO3 facies. Limited dispersion of these clusters towards Ca–Mg–SO4 or mixed facies may suggest the influence of secondary factors, such as evaporate dissolution or anthropogenic pollution sources. The relatively compact clustering pattern indicates that there is a moderate variability among villages, without abrupt transition towards Na–Cl type waters. V4–V6 demonstrate relatively elevated sulfate concentrations, probably showing localized evaporate dissolution or discharge from agricultural runoff. Conversely, bicarbonate dominates in villages V1–V3, a characteristic typical of carbonate weathering processes associated with glacial and alluvial deposits in northern Kazakhstan (Figure 8).

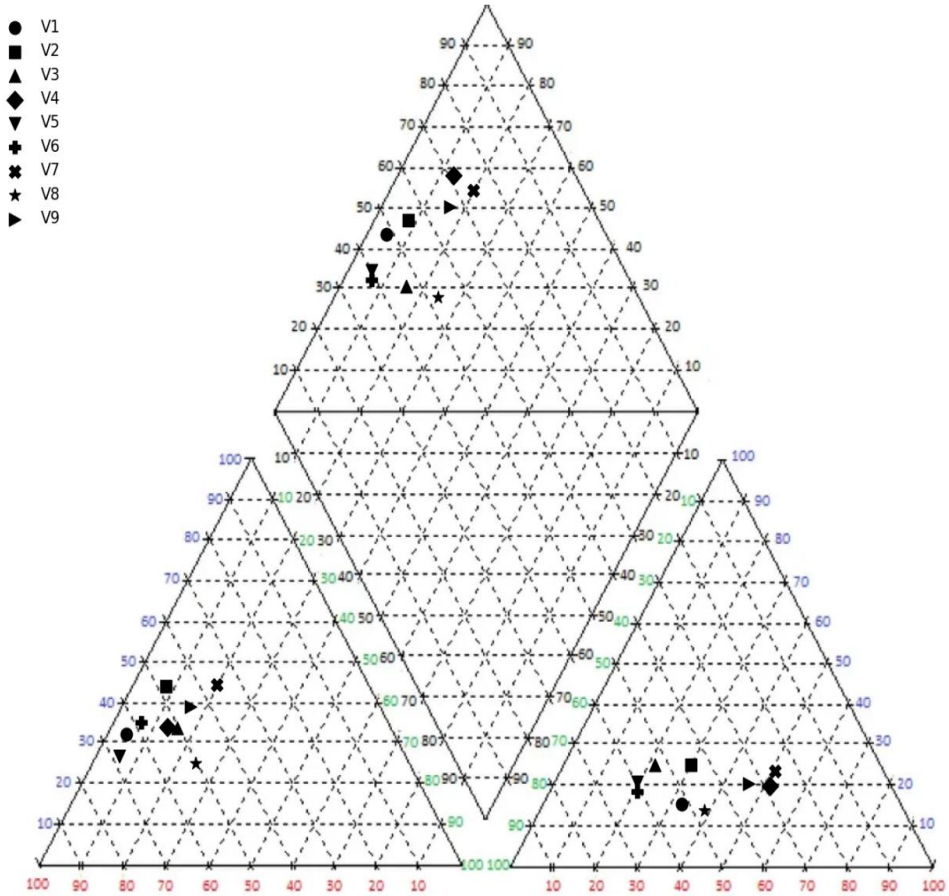


Figure 8. Piper diagram showing the hydrochemical facies distribution of groundwater samples across nine villages (V1–V9) of the Akmola region

Note: Different marker shapes represent individual villages. V1-Ortaagash; V2-Karabulak; V3-Malik Gabdullin; V4-Uyaly; V5-Zhanteke; V6-Karaegyn; V7-Iliynka; V8-Karazhar; V9-Taitobe

The Akmola region data includes detailed ion composition (Ca, Mg, HCO_3, Cl, SO_4, Na, K). Calculated TDS was approximately from 800 to 5000 mg/L, indicating varying levels of mineralization across villages. In the Akmola region, TDS calculated on the basis of the most significant ion concentrations showed high variance among villages, showing strong hydrogeological regulation of mineralization. The boxplot of TDS concentration in nine villages shows significant difference. Village Iliynka has extreme variance and high concentrations (>5000 mg/L), suggesting severe mineralization. Villages Karabulak and Taitobe also have higher median values of TDS than the remaining ones. At the same time, Malik Gabdullin, Uyaly, Zhanteke, Karaegyn and Karazhar have lower and stable mineralization rates. This shows significant within-regional water quality differences, indicating hydrogeochemical or possibly anthropogenic factors at the local level (Fig. 9).

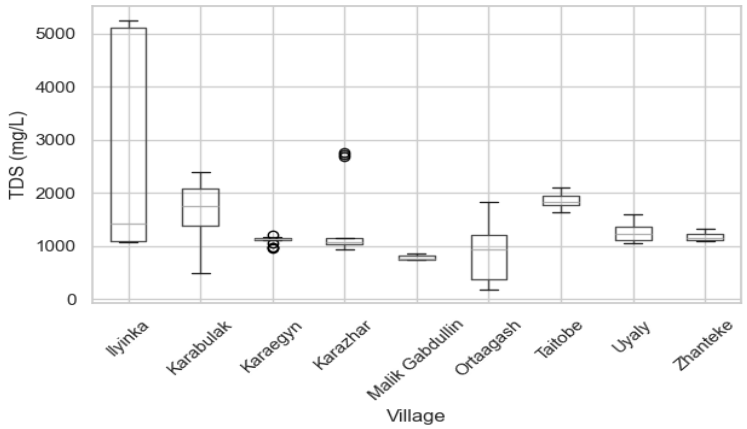


Figure 9. Boxplot of spatial variation of total dissolved solids (TDS, mg/L) across villages of Akmola region

This stacked bar chart depicts the frequency of groundwater samples grouped into different TDS categories in nine villages of the Akmola region. Most localities are dominated by samples with moderate mineralization, reflecting a general presence of elevated dissolved solids. Village V7 is distinguished by a sample classified as highly mineralized, indicating localized salinization. Conversely, samples from village V3 are predominantly of slightly mineralized waters. Spatial heterogeneity across the study area highlights diverse hydrochemical conditions (Figure 10).

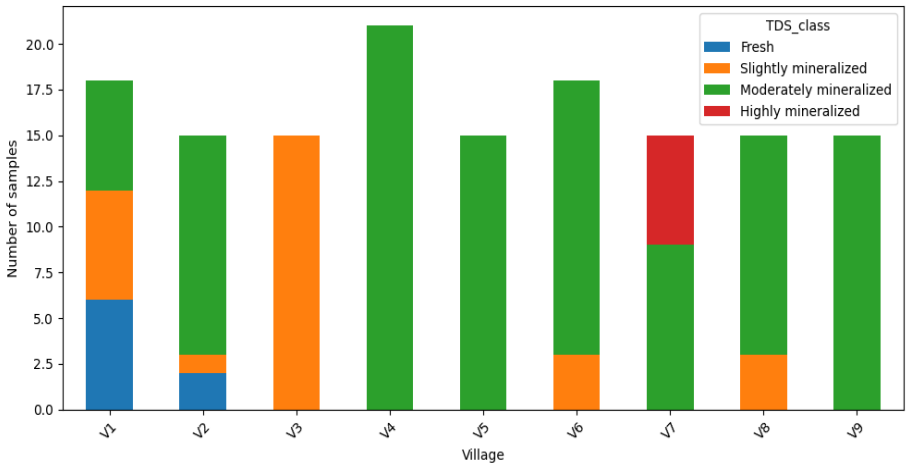


Figure 10. TDS classes of the Akmola region's villages of Kazakhstan

Note: V1-Ortaagash; V2-Karabulak; V3-Malik Gabdullin; V4-Uyaly; V5-Zhanteke; V6-Karaegyn; V7-Iliynka; V8-Karazhar; V9-Taitobe

In Figure 11, a comparative distribution of TDS concentrations in water samples taken in the Zhambyl region and the Akmola region is shown. TDS is a key hydrochemical characteristic which characterizes the degree of water mineralization and the content of dissolved inorganic substances. As a result, it is obvious that the TDS levels in the study region varied significantly. In the Zhambyl region, the concentrations of total dissolved solids (TDS) are relatively low, characterized by a narrower range and distribution curve. Most values fall within the 200 to 400 mg/L range, with a median value of about 300 mg/L. The relatively small variation in TDS data suggests a fairly stable hydrochemical regime. Conversely, in the Akmola region, TDS concentrations are substantially higher and exhibit greater variability. The median TDS value is more than 1100 mg/L, and the data's interquartile range demonstrates significant variation in water mineralization among the sampling points. Additionally, a number of extreme values greater than 5000 mg/L are observed, suggesting that certain localities are affected by high mineralization. The larger variation range and median TDS values in the Akmola region demonstrate a more heterogeneous hydrochemical regime than in the Zhambyl region. The reasons for these differences probably include specific geological features, the composition of the water supply and the environment.

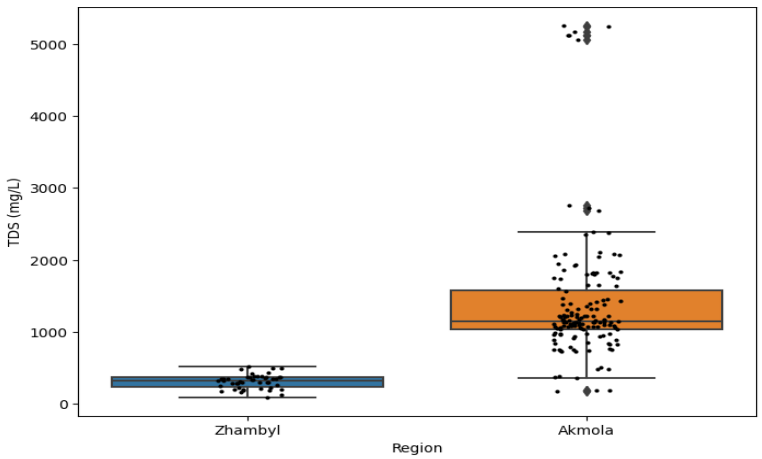


Figure 11. Distribution of TDS in research area of the Zhambyl and Akmola region of Kazakhstan

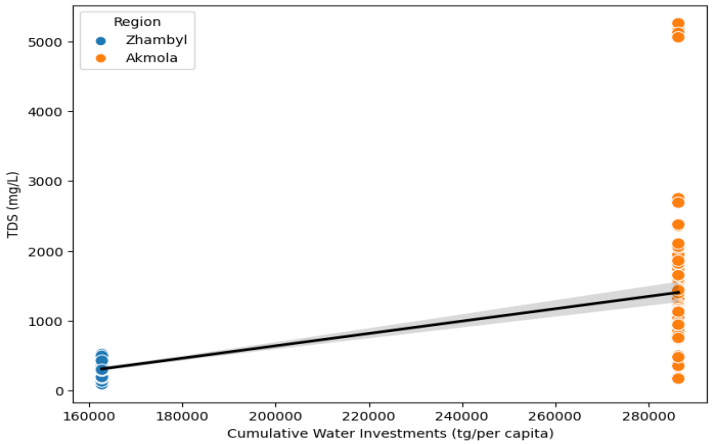


Figure 12. Relationship between cumulative environmental investment per capita and TDS concentrations in the Zhambyl and Akmola regions of Kazakhstan

Figure 12 shows the relationship between total environmental investments per capita and TDS concentrations in rural areas of the Zhambyl and Akmola regions. There are significant differences between the two regions. Zhambyl received an overall lower amount of investment (approximately 160,000 tenge per capita), however, their TDS values remained relatively moderate (100–500 mg/L). The clustering of the results within a relatively narrow range indicates less variability in water salinity across rural settlements. Conversely, the Akmola region received a higher level of total investment (approximately 285,000 tenge per capita), but also significantly higher TDS concentrations (200 mg/L–5000+mg/L). The results are also considerably dispersed, which indicates high variability in water salinity.

However, this relationship does not imply that increased spending directly causes higher mineralization. It is more likely a reflection of regional differences in geology, water composition and other factors inherent to the quality of a specific water supply system. For example, if groundwater in a particular area is naturally more mineralized, higher capital investments may be required to deliver water of acceptable quality to the population, or to install treatment facilities or monitoring systems to control water quality. The consistency of the findings obtained from trend analysis, non-parametric statistical tests, and hydrochemical interpretation indicates that the main conclusions are robust across different analytical approaches.

3.2. Discussion

3.2.1. Regional controls on water quality

This paper provides valuable insights into the relationship between environmental spending and water quality in rural areas of Kazakhstan and is a contribution to the scientific debate about sustainable territorial development and environmental management. The results indicate that environmental expenditure does not automatically ensure an adequate improvement of water quality in rural Kazakhstan and the achievement of sustainable development goals. Such experience is in alignment with existing international practice, which states that the effectiveness of public expenditure targeted towards water quality depends more on the efficient allocation of finances rather than on their amount. In 2015, the Organization for Economic Cooperation and Development (OECD) [47] accentuated on the fact that poorly targeted investments in water infrastructure and management may not provide anticipated results, even with large investments in water supply projects. Our results suggest that compatibility with the specific environmental and socio-economic conditions of the area are of the same importance as the amount of expenditure in regards to environmental effectiveness. It is important in our pursuit of Sustainable Development Goal 6 to accompany increased funding by effective governance, advanced technologies, and environmental and climatic specificities. The observed relationship between public environmental expenditure and rural water quality should be interpreted through an indirect mechanism rather than as a direct causal effect of financial inputs. Public environmental expenditure can potentially improve water quality through several intermediate pathways, including modernization of water supply infrastructure,

installation and upgrading of treatment facilities, protection of drinking water sources, improvement of monitoring systems, and maintenance of distribution networks. However, the extent to which these financial inputs translate into measurable improvements in water quality depends on the environmental and institutional context in which the investments are implemented. Regional hydrogeological conditions, baseline mineralization of source water, climatic variability, infrastructure condition, and management efficiency may therefore moderate the relationship between expenditure and observed hydrochemical outcomes.

Socioeconomic conditions may further moderate the relationship between public environmental expenditure and rural water-quality outcomes. Settlement size and remoteness, population density, household income, accessibility of centralized water-supply systems, agricultural activity, and local institutional capacity may influence both the allocation of environmental expenditure and the effectiveness of implemented water-management measures. In sparsely populated or remote rural settlements, for example, higher per-capita infrastructure costs and limited technical capacity may reduce the efficiency with which public expenditure is translated into improvements in water services. Agricultural intensity may additionally affect source-water quality through irrigation return flows and diffuse pollution. These factors were not directly incorporated into the present analysis because comparable village-level socioeconomic and investment data were unavailable; therefore, they should be regarded as potential moderating variables rather than empirically established causal mechanisms in this study.

This mechanism provides a plausible interpretation of the contrasting patterns observed in Akmola and Zhambyl. Akmola received substantially higher cumulative environmental investment per capita, yet its rural water samples exhibited higher and more variable TDS concentrations, including values exceeding 5,000 mg/L in some localities. In contrast, Zhambyl showed lower cumulative environmental expenditure but generally lower and less variable TDS concentrations. These findings should not be interpreted as evidence that higher expenditure deteriorates water quality. Rather, they suggest that regions facing less favorable baseline hydrogeological conditions may require greater financial resources to achieve comparable water quality outcomes. In this context, higher expenditure in Akmola may partly reflect greater environmental and infrastructural challenges rather than lower investment effectiveness alone. An important contribution of our study is its ability to pinpoint disparities between the Zhambyl and Akmola regions. The Zhambyl region exhibited comparatively better rural water quality despite lower cumulative environmental expenditure, whereas Akmola combined higher expenditure with substantially greater TDS concentrations and spatial variability. These differences are consistent with the influence of contrasting hydrogeological and climatic conditions; however, the available data do not allow their individual causal contributions to be isolated. The Akmola region, on the other hand, is characterized by harsher climatic conditions that potentially limits the natural ability of water systems to purify themselves. As a result, even with high rates of investments, maintaining good quality of water in the Akmola region proved to be difficult. Such circumstances highlight the need for a region-specific, climate-sensitive approach in addressing environmental challenges. The World Bank [48] argues that “water investments should also be tailored to local environmental and institutional conditions, as water quality may be significantly reduced by climatic or geographical limitations” [48]. Moreover, hydro-geological conditions impact water quality in specific areas with high levels of TDS in areas that have water-logged soil, which affects natural filtration mechanisms and creates further environmental degradation. These are aspects that often play a role in policy formulation but are often neglected in achieving long-term environmental sustainability. Recent studies emphasize that decentralized water recovery technologies may substantially improve water security in rural areas, although their effectiveness depends on local institutional, technical, and economic conditions [49].

In the context of territorial development, these findings highlight that infrastructure alone cannot promote equal access to safe drinking water for all rural households. While infrastructure may be similar on a territorial scale, there are significant disparities in environmental and climatic conditions that impact the ability of rural areas to provide clean water in practice. While rural areas in southern Kazakhstan benefit from milder environmental conditions which allow the infrastructure to perform better and make it more accessible, rural communities in

the northern and more northern parts of Kazakhstan face environmental constraints that increase the costs and complexity of infrastructure delivery, possibly resulting in the aggravation of territorial disparities. These results have important implications for the sustainable development of rural areas and achieving environmental justice. They indicate that in order to achieve better environmental sustainability, a single approach may not address existing disparities, but rather, policies need to be tailored and context-specific to improve rural resilience and ensure that rural communities receive better access to clean, safe drinking water. Public environmental expenditure primarily supports infrastructure modernization, monitoring systems, and water treatment facilities. However, the effectiveness of these investments depends on regional hydrogeological conditions, climatic variability, infrastructure age, and institutional management. Consequently, identical investment volumes may produce different environmental outcomes across regions. These results also contribute to the literature on rural development challenges and disparities around the world. In particular, rural areas are still the most underserved and face the most obstacles in achieving safe, sustainable access to water, often due to infrastructural challenges and climatic, environmental variability. Our findings are specific to Kazakhstan, however, they could be applicable in the context of other countries with diverse climatic conditions that face similar difficulties in rural development. Our results are also a reflection of a more global issue regarding challenges of integrating environmental, economic and social concerns in the context of environmental development [50].

The present findings are broadly consistent with previous studies showing that the environmental outcomes of water-sector investments depend on more than the absolute amount of financial expenditure. Previous research has demonstrated that investment effectiveness is conditioned by governance quality, infrastructure performance, environmental constraints, and the prioritization of financial resources [20], [23]. Our results support this interpretation: despite substantially higher cumulative environmental expenditure in Akmola, rural water samples exhibited higher and more variable mineralization than in Zhambyl. At the same time, our findings extend previous research by demonstrating this relationship under the contrasting hydrogeological and climatic conditions of rural Kazakhstan. Unlike studies that primarily evaluate financial efficiency or infrastructure performance, the present study combines long-term regional expenditure data with field-based hydrochemical measurements. However, because expenditure data are available at the regional level whereas water-quality observations are village-specific and cross-sectional, the observed differences should be interpreted as regional associations rather than evidence of a direct causal effect of public expenditure on water quality. An additional consideration is the possibility of endogenous investment allocation. Regions experiencing more severe environmental or infrastructure constraints may receive higher levels of public expenditure precisely because their baseline conditions require greater intervention. Consequently, the positive coexistence of high expenditure and unfavorable water-quality indicators should not be interpreted as evidence of ineffective spending without accounting for initial environmental conditions and investment targeting. The present cross-sectional water-quality data do not allow this mechanism to be tested causally; nevertheless, it provides an important explanation for the observed regional pattern and should be considered when evaluating the effectiveness of public environmental expenditure.

4. Conclusions

The comparative analysis of the Akmola and Zhambyl regions revealed marked regional differences in both public environmental expenditure and rural drinking-water quality. Environmental expenditure per capita increased significantly during 2015–2024 in both regions, but at different rates. The estimated annual increase was 3,439.95 tenge/person/year in Akmola ($R^2 = 0.626$, $p = 0.0064$) and 1,944.97 tenge/person/year in Zhambyl ($R^2 = 0.700$, $p = 0.0026$), with both trends independently confirmed by the Mann–Kendall test ($p < 0.01$). Despite the higher expenditure level and faster growth observed in Akmola, TDS concentrations were substantially higher and more variable, with a median above 1,100 mg/L and values exceeding 5,000 mg/L at some sampling locations, whereas most TDS values in Zhambyl were approximately 200–400 mg/L. The observed differences in water-quality outcomes between the two regions are associated with contrasting hydrogeological, climatic, infrastructural, and management contexts. However, the present study does not establish the individual causal

contribution of these factors. Accordingly, the coexistence of higher environmental expenditure and higher TDS concentrations in Akmola should not be interpreted as evidence that greater expenditure causes poorer water quality. Rather, the results indicate that different levels and trajectories of public environmental expenditure coexist with markedly different hydrochemical conditions and that regional environmental context should be considered when interpreting expenditure–water quality relationships.

The scientific contribution of this study lies in providing comparative regional evidence of a mismatch between the magnitude and trajectory of public environmental expenditure and observed rural water-quality outcomes under contrasting environmental conditions in Kazakhstan. By combining long-term regional expenditure trends with field-based hydrochemical measurements, the study shows that expenditure levels alone cannot serve as a proxy for rural water-quality outcomes. The findings therefore extend the limited empirical evidence from Central Asia concerning the relationship between public environmental expenditure and rural drinking-water quality. From a policy perspective, the findings support a more regionally differentiated approach to the allocation and evaluation of environmental expenditure. Rather than relying solely on expenditure volumes or uniform funding approaches, water-management planning could take into account local hydrogeological conditions, baseline water mineralization, infrastructure status, and monitoring needs. In Akmola, where TDS exceeded 5,000 mg/L at some sampling locations, particular attention may be warranted for treatment options suitable for highly mineralized water, source-water protection, and targeted water-quality monitoring. These recommendations represent policy implications derived from the observed regional patterns and should not be interpreted as evidence of the effectiveness of specific interventions, which was not directly tested in this study. Several important limitations should be acknowledged. First, the study covers only two regions of Kazakhstan and therefore does not support nationwide generalization. Second, hydrochemical observations were obtained during a single sampling period, preventing assessment of temporal changes in water quality. Third, environmental expenditure was measured at the regional level, whereas water-quality observations were collected at the village level, creating a spatial-scale mismatch that prevents direct attribution of village-level water-quality outcomes to regional expenditure. Village-level investment data were also unavailable, and public expenditure allocation may be endogenous because regions facing greater environmental or infrastructure constraints may receive higher levels of investment. Therefore, the findings should be interpreted as comparative regional associations rather than causal effects. Future research should combine repeated village-level water-quality measurements with spatially disaggregated investment data, expand the analysis to additional regions of Kazakhstan and other Central Asian countries, integrate spatial and remote-sensing information, and apply appropriate causal inference methods where longitudinal data are available.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

Funding information

Supported by grant No. AP26104279 "Ecological and economic efficiency of rational use of water resources in conditions of water scarcity" of the "Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan."

Acknowledgements

Collate acknowledgements in a separate section at the end of the article before the references and do not, include them on the title page, as a footnote to the title or otherwise. List here those institutions or individuals who provided help during the research.

Author contribution

The contribution to the paper is as follows: R. Beisenova, A. Zhupysheva: study conception and design; A. Mashayeva: data collection; A. Zhupysheva, N.Zholamanov. B. Ashimova: analysis and interpretation of

results; A. Zhupysheva, A.Mashayeva: draft preparation. All authors approved the final version of the manuscript.

References

[1] C. Benoît et al., "The guidelines for social life cycle assessment of products: just in time!," Int. J. Life Cycle Assess., vol. 15, no. 2, pp. 156–163, Feb. 2010, https://doi.org/10.1007/s11367-009-0147-8.

[2] L. Tozzini, A. Pannunzio, and P. T. Soria, "Water footprint of soybean, maize and wheat in Pergamino, Argentina," Agricultural Sciences, vol. 12, no. 3, pp. 305–323, Mar. 2021, https://doi.org/10.4236/as.2021.123020.

[3] A. K. Gain, C. Giupponi, and Y. Wada, "Measuring global water security towards sustainable development goals," Environ. Res. Lett., vol. 11, no. 12, Art. no. 124015, Dec. 2016, https://doi.org/10.1088/1748-9326/11/12/124015.

[4] C. Garcia, P. A. López-Jiménez, M. Pérez-Sánchez, and R. Sanchis, "Methodology for assessing progress in sustainable development goals indicators in urban water systems. How far are we from the 2030 targets?," Sustain. Cities Soc., vol. 112, p. 105616, Oct. 2024, https://doi.org/10.1016/j.scs.2024.105616.

[5] K. Carden and N. Armitage, "Assessing urban water sustainability in South Africa—not just performance measurement," Water SA, vol. 39, no. 3, pp. 345–360, Jul. 2013, https://doi.org/10.4314/wsa.v39i3.1.

[6] O. Romano and A. Akhmouch, "Water governance in cities: Current trends and future challenges," Water, vol. 11, no. 3, Art. no. 500, Mar. 2019, https://doi.org/10.3390/w11030500.

[7] M. Chen et al., "Unveiling impacts and optimal strategies of water-saving system for integrated water resources management in a water-scarce watershed," J. Environ. Manage., vol. 373, p. 123435, Jan. 2025, https://doi.org/10.1016/j.jenvman.2024.123435.

[8] K. G. Magbondé, D. R. Thiam, and N. Wagner, "The economic impacts of rural water supply infrastructures in developing countries: Empirical evidence from Senegal," Environ. Resour. Econ., vol. 87, no. 10, pp. 2571–2628, Oct. 2024, https://doi.org/10.1007/s10640-024-00897-4.

[9] M. S. Poustie, N. Frantzeskaki, and R. R. Brown, "A transition scenario for leapfrogging to a sustainable urban water future in Port Vila, Vanuatu," Technol. Forecast. Soc. Change, vol. 105, pp. 129–139, Apr. 2016, https://doi.org/10.1016/j.techfore.2015.12.008.

[10] W. Pot, "Deciding for resilience: Utilizing water infrastructure investments to prepare for the future," WIREs Water, vol. 10, no. 5, Art. no. e1661, Sep. 2023, https://doi.org/10.1002/wat2.1661.

[11] T. H. F. Wong, B. C. Rogers, and R. R. Brown, "Transforming cities through water-sensitive principles and practices," One Earth, vol. 3, no. 4, pp. 436–447, Oct. 2020, https://doi.org/10.1016/j.oneear.2020.09.012.

[12] R. R. Weerasooriya et al., "Industrial water conservation by water footprint and sustainable development goals: a review," Environ. Dev. Sustain., vol. 23, no. 9, pp. 12661–12709, Sep. 2021, https://doi.org/10.1007/s10668-020-01184-0.

[13] D. Liang, H. Lu, L. Feng, L. Qiu, and L. He, "Assessment of the sustainable utilization level of water resources in the Wuhan metropolitan area based on a three-dimensional water ecological footprint model," Water, vol. 13, no. 24, Art. no. 3505, Dec. 2021, https://doi.org/10.3390/w13243505.

[14] N. S. Kakwani and P. P. Kalbar, "Prioritization of strategies for urban water circular economy using water circularity indicator," Water Policy, vol. 26, no. 5, pp. 480–505, May 2024, https://doi.org/10.2166/wp.2024.233.

[15] C. Bosco, K. Nessler Seglem, E. Sivertsen, O. Jovanović, and H. Helness, "Developing a framework to assess water smartness and sustainability of circular economy solutions in the water sector," J. Clean. Prod., vol. 517, p. 145874, Jul. 2025, https://doi.org/10.1016/j.jclepro.2025.145874.

[16] R. Zhang, C.-C. Lu, J.-H. Lee, Y. Feng, and Y.-H. Chiu, "Dynamic Environmental Efficiency Assessment of Industrial Water Pollution," Sustainability, vol. 11, no. 11, p. 3053, May 2019, https://doi.org/10.3390/su11113053.

[17] OECD, OECD Annual Report 2003. Paris, France: OECD Publishing, 2003, https://doi.org/10.1787/annrep-2003-en

[18] Z. Wang, R. Ouyang, Y. Li, H. Wang, and Z. Cheng, "Investigating the financialization of water infrastructure in China: A public policy perspective," Water Policy, vol. 26, no. 5, pp. 506–523, May 2024, https://doi.org/10.2166/wp.2024.256.

[19] N. Reis, G. Vargas Magaña, and S. Vélez Villegas, "Water, finance and financialisation: A review," Water Alternatives, vol. 17, no. 2, pp. 266–291, 2024.

[20] P. A. Green et al., "Mapping a sustainable water future: Private sector opportunities for global water security and resilience," Global Environmental Change, vol. 88, p. 102906, Sep. 2024, https://doi.org/10.1016/j.gloenvcha.2024.102906.

[21] M. Macchiaroli, L. Dolores, and G. De Mare, "Multicriteria decision making and water infrastructure: An application of the analytic hierarchy process for a sustainable ranking of investments," Appl. Sci., vol. 13, no. 14, Art. no. 8284, Jul. 2023, https://doi.org/10.3390/app13148284.

[22] Z. Stoyanova, "The efficiency of financial support for water infrastructure improvement in Bulgaria," Econ. Agric., vol. 69, no. 4, pp. 961–974, 2022, https://doi.org/10.5937/ekoPolj2204961S.

[23] H. Chen et al., "Long-term water quality dynamics and influencing factors under ecological compensation mechanisms: A case study of China's first cross-provincial ecological compensation watershed," J. Environ. Manage., vol. 380, p. 125142, Apr. 2025, https://doi.org/10.1016/j.jenvman.2025.125142.

[24] H. Zhong, M. H. Taylor, K. S. Rollins, D. T. Manning, and C. G. Goemans, "Who pays for water scarcity? Evaluating the welfare implications of water infrastructure investments for cities," Ann. Reg. Sci., vol. 63, no. 3, pp. 559–600, Dec. 2019, https://doi.org/10.1007/s00168-019-00943-w.

[25] C. lo Storto, "Performance evaluation of water services in Italy: A meta-frontier approach accounting for regional heterogeneities," Water, vol. 14, no. 18, Art. no. 2882, Sep. 2022, https://doi.org/10.3390/w14182882.

[26] M. Molinos-Senante and A. Maziotis, "A dynamic framework for benchmarking sustainability in water utilities," Cleaner Environmental Systems, vol. 19, p. 100368, Dec. 2025, https://doi.org/10.1016/j.cesys.2025.100368.

[27] H. Sakai, "Review of research on performance indicators for water utilities," AQUA — Water Infrastructure, Ecosystems and Society, vol. 73, no. 2, pp. 167–182, Feb. 2024, https://doi.org/10.2166/aqua.2024.224.

[28] L. A. Wendling, A. Huovila, M. zu Castell-Rüdenhausen, M. Hukkalainen, and M. Airaksinen, "Benchmarking nature-based solution and smart city assessment schemes against the Sustainable Development Goal indicator framework," Front. Environ. Sci., vol. 6, Art. no. 69, Jul. 2018, https://doi.org/10.3389/fenvs.2018.00069.

[29] M. Osorio, M. Cobo, and N. Sanchez, "Assessing social and energy vulnerabilities through a novel S-LCA approach: A rural case study in Colombia's Pacific region," Int. J. Life Cycle Assess., vol. 30, no. 12, pp. 3536–3559, Dec. 2025, https://doi.org/10.1007/s11367-025-02535-7.

[30] C. Kennedy, M. Zhong, and J. Corfee-Morlot, “Infrastructure for China’s ecologically balanced civilization,” Engineering, vol. 2, no. 4, pp. 414–425, Dec. 2016, https://doi.org/10.1016/j.eng.2016.04.014.

[31] J. Chen, G. Tian, J. Li, and H. Xu, “Research on the Outgoing Audit and Evaluation of Water Resource Assets of Leadership Cadres in City Y,” Sustainability, vol. 15, no. 16, p. 12535, Aug. 2023, https://doi.org/10.3390/su151612535.

[32] R. Beisenova et al., “Perceived and physical quality of drinking water in Pavlodar and Akmola rural regions of Kazakhstan,” Sustainability, vol. 16, no. 17, Art. no. 7625, Sep. 2024, https://doi.org/10.3390/su16177625.

[33] Z. Tekebayeva et al., “Ecological assessment of phytoplankton diversity and water quality to ensure the sustainability of the ecosystem in Lake Maybalyk, Astana, Kazakhstan,” Sustainability, vol. 16, no. 22, Art. no. 9628, Nov. 2024, https://doi.org/10.3390/su16229628.

[34] V. M. Kotlyakov, V. M. Razumovskii, and A. O. Brinken, “The Russian geographic society turns 160,” Her. Russ. Acad. Sci., vol. 76, no. 2, pp. 166–171, Mar. 2006, https://doi.org/10.1134/S1019331606020109.

[35] A. Nugmanov, R. Beisenova, A. Kali, A. Zhupysheva, I. Shamshidin, and D. Beisenova, “Linking perceived and actual drinking water quality across rural landscapes of northern Kazakhstan,” Front. Environ. Sci., vol. 14, Feb. 2026, Art. no. 1731716, https://doi.org/10.3389/fenvs.2026.1731716.

[36] Kazakh Encyclopediasy Limited Liability Partnership, Казахстан : национальная энциклопедия, 1st ed., vol. 3. Almaty: Главная редакция «Казак энциклопедиясы», 2005.

[37] Department of Population Statistics, “Population of the Republic of Kazakhstan by gender and type of locality (at the beginning of 2024).” Accessed: Jul. 08, 2026. [Online]. Available: https://stat.gov.kz/en/industries/social-statistics/demography/publications/157662/

[38] K. Zh. Uzakpaeva, N. I. Kazantseva, O. Ya. Poletkina, and T. A. Shevchenko, “Путеводитель” [Guidebook], State Archives of Akmola Region. Accessed: Jul. 7, 2026. [Online]. Available: https://web.archive.org/web/20180423170511/http://www.netref.ru/putevoditele.html?page=15#2

[39] J. I. Drever, The Geochemistry of Natural Waters: Surface and Groundwater Environments, 3rd ed. Upper Saddle River, NJ, USA: Prentice Hall, 2002. [Online]. Available: https://gw-project.org/books/the-geochemistry-of-natural-waters/

[40] J. D. Hem, Study and Interpretation of the Chemical Characteristics of Natural Water, 3rd ed., U.S. Geological Survey Water-Supply Paper 2254. Reston, VA, USA: U.S. Geological Survey, 1985, https://doi.org/10.3133/wsp2254.

[41] M. Y. Jat Baloch et al., “Shallow Groundwater Quality Assessment and Its Suitability Analysis for Drinking and Irrigation Purposes,” Water (Basel)., vol. 13, no. 23, p. 3361, Nov. 2021, https://doi.org/10.3390/w13233361.

[42] M. Y. Jat Baloch et al., “Hydrogeochemical Mechanism Associated with Land Use Land Cover Indices Using Geospatial, Remote Sensing Techniques, and Health Risks Model,” Sustainability, vol. 14, no. 24, p. 16768, Dec. 2022, https://doi.org/10.3390/su142416768.

[43] M. Jat Baloch et al., “Evolution mechanism of arsenic enrichment in groundwater and associated health risks in southern Punjab, Pakistan,” Int. J. Environ. Res. Public Health, vol. 19, no. 20, Art. no. 13325, Oct. 2022, https://doi.org/10.3390/ijerph192013325.

[44] M. Y. Jat Baloch et al., “Groundwater contamination, fate, and transport of fluoride and nitrate in Western Jilin, China: Implications for water quality and health risks,” Environ. Chem. Ecotoxicol., vol. 7, pp. 1189–1202, 2025, https://doi.org/10.1016/j.enceco.2025.04.010.

[45] R. Beisenova et al., “Influence of Geographical Locations on Drinking Water Quality in Rural Pavlodar Region, Kazakhstan,” Water (Basel)., vol. 17, no. 7, p. 945, Mar. 2025, https://doi.org/10.3390/w17070945.

[46] R. Beisenova et al., “Assessment of atmospheric air quality in the region of Central Kazakhstan and Astana,” Atmosphere, vol. 14, no. 11, Art. no. 1601, Oct. 2023, https://doi.org/10.3390/atmos14111601.

[47] OECD, OECD Guidelines on Corporate Governance of State-Owned Enterprises, 2015 ed. Paris, France: OECD Publishing, 2015, https://doi.org/10.1787/9789264244160-en.

[48] World Bank, World Development Report 2017: Governance and the Law. Washington, DC, USA: World Bank, 2017, https://doi.org/10.1596/978-1-4648-0950-7.

[49] United Nations, The United Nations World Water Development Report 2021: Valuing Water. Paris, France: UNESCO, 2021, https://doi.org/10.54679/MOMU6572.

[50] J. González-Camejo, L. De Simoni, N. Kamergi, E. Mino, A. L. Eusebi, and F. Fatone, “Worldwide replicability of alternative water recovery technologies to close water loops in decentralised populations,” J. Environ. Manage., vol. 384, p. 125481, Jun. 2025, https://doi.org/10.1016/j.jenvman.2025.125481.