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Research Article

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Posted Date: September 29th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-9782037/v1>

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Additional Declarations: No competing interests reported.

Integrated Geoecological Monitoring and Environmental Risk Assessment of Potash Industrial Facilities under Arid Climatic Conditions

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Abstract: Potash industry facilities located in arid climatic regions represent major sources of technogenic geoecological transformation due to intensive mining activities, halite waste accumulation, aerosol emissions, and secondary salinization processes. Under arid environmental conditions, limited precipitation, high evaporation rates, and intensive wind activity significantly intensify the atmospheric transport of saline aerosols and the spatial expansion of technogenic impacts. Despite extensive international research on mining-related environmental degradation, integrated geoecological monitoring and environmental risk assessment systems for potash industrial regions under arid climates remain insufficiently developed.

This study aims to develop an integrated geoecological monitoring and environmental risk assessment framework for potash industrial facilities under arid climatic conditions using the Dehqonobod potash industrial region in southern Uzbekistan as a case study. Comprehensive geoecological investigations were conducted to evaluate technogenic transformations affecting atmospheric, pedospheric, and hydrospheric components. Atmospheric aerosol dispersion, soil salinization, hydrochemical transformation, and spatial risk differentiation were analyzed using field observations, GIS technologies, spatial interpolation, correlation analysis, and scenario-based environmental modeling approaches.

The results demonstrated that halite waste dumps function as long-term sources of saline aerosol emissions under arid conditions. PM₁₀ concentrations decreased from 185 µg/m³ near waste storage zones to 25 µg/m³ at a distance of 10 km, indicating exponential aerosol attenuation with increasing distance from emission sources. Soil salinity analysis revealed pronounced spatial differentiation of secondary salinization processes, with electrical conductivity

values exceeding 8 dS/m in highly impacted zones. Regression analysis showed a strong inverse relationship between salinity intensity and distance from technogenic sources ($R^2 = 0.92$). Hydrochemical assessment identified elevated TDS, Na^+ , and Cl^- concentrations in areas adjacent to halite waste dumps, confirming active technogenic salt migration into surface and groundwater systems. Correlation analysis revealed strong positive relationships between atmospheric aerosol load, soil salinity, and hydrochemical indicators ($r = 0.86\text{--}0.97$), confirming the integrated nature of geoecological transformation processes.

GIS-based Geoecological Impact Index (GEI) analysis enabled the delineation of high-, moderate-, and low-risk zones around potash industrial facilities. The highest environmental risk levels were identified within a 0–3 km radius surrounding halite waste dumps and processing complexes. The proposed integrated monitoring and risk assessment framework provides a scientifically grounded basis for environmental management, reclamation planning, and sustainable geoecological monitoring of potash industry facilities under arid climatic conditions.

Keywords: Arid climate; Potash industry; Geoecological monitoring; Saline aerosol migration; Secondary salinization; Hydrochemical transformation; GIS-based risk assessment; Geoecological Impact Index (GEI).

1. Introduction

In recent decades, the rapid development of the mining and chemical industries worldwide has significantly increased the demand for potash fertilizers. As a result, environmental impacts associated with potash ore extraction, processing, transportation, and waste disposal have become major global geoecological concerns. Potash industrial facilities are characterized by complex technogenic transformations, including atmospheric pollution, accumulation of saline waste, soil degradation, hydrogeochemical alteration, and the formation of technogenic landscapes (Goudie & Middleton; 2006 Shao, 2008).

The geoecological risk associated with potash industrial activities is particularly pronounced under arid climatic conditions. In such environments, limited precipitation, high evaporation rates, intensive wind activity, and the low resilience of natural ecosystems accelerate the development and spatial expansion of technogenic processes. In particular, the open-air storage of halite waste and saline tailings promotes long-distance atmospheric transport of saline aerosol particles. Consequently, secondary soil salinization, mineralization of surface and groundwater resources, degradation of biological environments, and reduction of geoecological stability become increasingly significant environmental problems (Sparks, 2003; Alloway, 2013; Qadir et al., 2014; Middleton, 2017). Recent studies demonstrate that soil salinization under arid climatic conditions represents one of the most rapidly expanding forms of land degradation worldwide (Shokri, 2024). Similar salinization monitoring challenges under arid climatic conditions were also reported for irrigated regions of Central Asia (Jumaniyazov et al., 2024).

International studies investigating the environmental impacts of potash industrial facilities have primarily been conducted in Canada, Belarus, Germany, Russia, and China. Previous research has mainly focused on saline water infiltration, hydrochemical transformation, and environmental risks associated with tailings storage systems (Kostecki & Ignatiuk, 2012). However, most of these studies were performed under humid or semi-humid climatic conditions, whereas geoecological processes characteristic of arid environments – particularly atmospheric saline aerosol migration, secondary salinization, and the spatial differentiation of technogenic impacts – remain insufficiently investigated. Although recent GIS- and remote sensing-based approaches have significantly improved salinity assessment capabilities, integrated geoecological monitoring frameworks combining atmospheric aerosol transport, hydrochemical transformation, and spatial risk zoning under arid industrial conditions remain poorly developed (Wang et al., 2024). Similar processes of groundwater salinization and secondary soil transformation around potash mining regions were also reported by Mitrakova and Khayrulina (2019). Recent investigations of potash mining regions additionally confirmed the integrated character of atmospheric, hydrological, and pedospheric degradation processes associated with halite waste accumulation and saline tailings storage (Ushakova et al., 2023).

Under arid conditions, atmospheric transport of technogenic saline aerosols can significantly affect soil physicochemical properties, biological productivity, and ecosystem stability. Wind-driven migration of saline particles may accelerate pedospheric degradation and biogeocenotic transformation processes in dryland landscapes (Shao, 2008; Xie et al., 2010). Therefore, the development of integrated approaches for geoecological monitoring, environmental risk zoning, and assessment of technogenic impacts in potash industrial regions located within arid environments represents an important scientific and practical challenge.

The Dehqonobod Potash Plant, located in the southern part of Uzbekistan, is one of the largest potash industrial facilities in Central Asia. Mining, ore processing, transportation, and halite waste disposal processes within the industrial complex exert complex technogenic impacts on atmospheric, hydrospheric, pedospheric, and biological systems. In particular, the open storage of halite waste creates favorable conditions for atmospheric saline aerosol dispersion and the development of secondary salinization processes.

The aim of this study is to develop an integrated geoecological monitoring and environmental risk assessment framework for potash industrial facilities under arid climatic conditions. The study evaluates the major technogenic impact factors, their influence on atmospheric, hydrospheric, pedospheric, and biological environments, and the spatial distribution patterns of geoecological processes. In addition, an integrated monitoring and environmental risk management approach is proposed to improve geoecological stability in arid industrial landscapes.

The study was conducted within the Dehqonobod Potash Plant industrial area and the Tyubegatan potash deposit located in southern Uzbekistan (Figure 1).

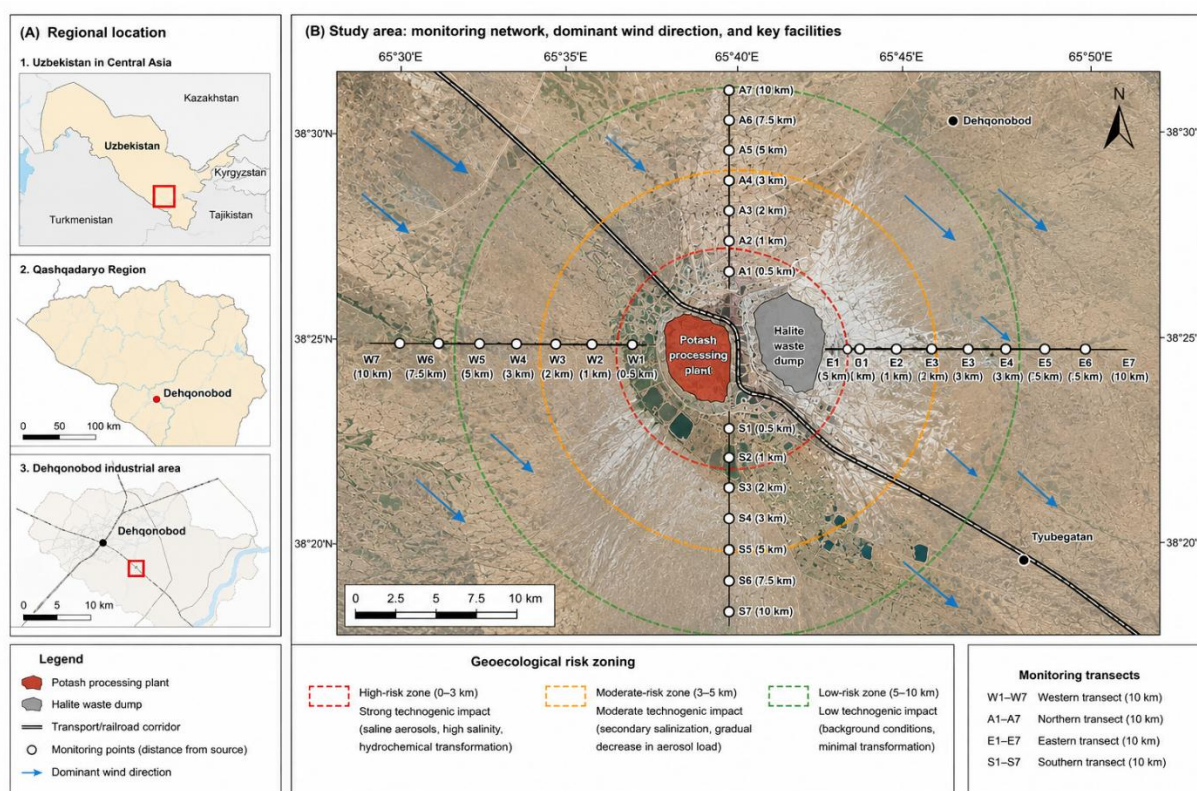


Fig. 1. Geographic setting, monitoring network, dominant wind direction, and integrated geoeological zoning framework of the Dehqonobod potash industrial region under arid climatic conditions.

The scientific novelty of this study lies in the development of an integrated geoeological monitoring and environmental risk assessment framework for potash industrial facilities located under arid climatic conditions. Unlike previous studies focused primarily on isolated hydrochemical or soil degradation processes, the present research integrates atmospheric aerosol dispersion modeling, soil salinization assessment, hydrogeoeological analysis, GIS–based spatial interpolation, and Geoeological Impact Index (GEI) evaluation within a unified geoeological system. The study further establishes quantitative relationships among atmospheric aerosol load, pedospheric salinization, and hydrospheric mineralization, demonstrating the interconnected nature of technogenic transformation processes in arid industrial landscapes. In addition, a GIS–based geoeological risk zoning approach is proposed for identifying high-, moderate-, and low-risk environmental zones surrounding halite waste dumps and potash industrial infrastructure.

2. Materials and Methods

2.1. Study Area and Geoeological Conditions

The study was conducted within the Dehqonobod potash industrial region located in southern Uzbekistan, including the Tyubegatan potash deposit, ore processing facilities, halite waste dumps, sludge storage zones, and associated transportation infrastructure.

The study area is characterized by an arid continental climate with low annual precipitation (200–300 mm/year), high evaporation intensity, and frequent wind activity. Average annual wind speed varies between 4 and 6 m/s, while episodic wind events may exceed 8–10 m/s during dry seasons. Such climatic conditions significantly enhance atmospheric transport of saline aerosol particles and intensify secondary salinization processes within surrounding landscapes.

The dominant natural landscapes are represented by semi-desert ecosystems with weakly developed gray-brown soils susceptible to technogenic salinization. Groundwater occurs at relatively deep levels; however, localized hydrochemical transformations may develop in areas adjacent to halite waste storage zones due to infiltration of mineralized leachates and dry deposition of saline aerosols.

2.2. Integrated Geoecological Monitoring Framework

An integrated geoecological monitoring framework was developed to evaluate technogenic impacts affecting atmospheric, pedospheric, and hydrospheric systems. The monitoring system combined:

- field observations;
- laboratory analyses;
- GIS-based spatial analysis;
- statistical assessment;
- scenario-based environmental modeling.

The methodological approach was designed to assess the interconnected nature of geoecological transformation processes developing around potash industrial facilities under arid climatic conditions.

Monitoring points were distributed along the dominant wind direction at distances of 0.5, 1, 2, 3, 5, 7.5, and 10 km from halite waste dumps and processing facilities. Spatial differentiation of geoecological indicators was evaluated using a distance-gradient approach.

2.3. Atmospheric Aerosol Assessment

Atmospheric conditions were evaluated based on PM_{2.5} and PM₁₀ concentrations, wind speed, wind direction, and spatial characteristics of saline aerosol migration.

Because long-term instrumental aerosol monitoring data were limited within the study region, atmospheric aerosol dispersion was assessed using a calibrated scenario-based dispersion modeling approach adapted to arid climatic conditions. Model parameters were calibrated according to regional wind regimes, halite particle properties, and published aeolian transport studies (Shao, 2008; Xie et al., 2010).

Spatial attenuation of aerosol concentration was evaluated using an exponential dispersion model:

$$C(x) = C_0 e^{-kx}$$

where: $C(x)$ – aerosol concentration at distance (x); C_0 – initial aerosol concentration near the emission source; k – aerosol attenuation coefficient; x – distance from the emission source.

To evaluate the influence of wind activity on saline aerosol migration, the model was modified as:

$$C(x, v) = C_0 e^{-kx} (1 + \alpha v)$$

where: v – wind speed; α – wind influence coefficient.

Under arid climatic conditions, the dispersion coefficient (k) was assumed within the range 0.1–0.3 depending on particle size and atmospheric stability conditions, while (α) ranged from 0.5 to 1.2 according to regional wind intensity.

2.4. Soil Salinization Assessment

Secondary soil salinization intensity was evaluated using electrical conductivity (ECe), Na^+ and Cl^- concentrations, and soil salinity indices.

Soil samples were assessed along the established monitoring transects surrounding technogenic facilities. Spatial interpolation of salinity distribution was performed using GIS-based interpolation methods.

The Soil Salinity Index (SI) was calculated as:

$$SI = \frac{EC}{EC_{crit}}$$

where: SI – soil salinity index; EC – measured electrical conductivity; EC_{crit} – critical salinity threshold (4 dS/m according to FAO standards).

Salinity classes were interpreted according to FAO salinity classification criteria.

2.5. Hydrogeoecological Assessment

Hydrogeoecological conditions were evaluated using hydrochemical indicators including:

- total dissolved solids (TDS);
- electrical conductivity (EC);
- Na^+ concentration;
- Cl^- concentration;
- SO_4^{2-} concentration.

Because continuous hydrochemical monitoring datasets were limited, hydrochemical conditions were additionally evaluated using scenario-based hydrogeochemical modeling calibrated to regional arid environmental conditions and published hydrochemical datasets from potash industrial regions.

Spatial hydrochemical gradients were analyzed relative to distance from halite waste storage facilities. Modeled datasets were primarily used to evaluate spatial geoecological trends and relative impact gradients rather than absolute environmental concentrations.

2.6. GIS-Based Spatial Analysis and Geoecological Risk Zoning

Spatial differentiation of geoecological impacts was analyzed using GIS technologies and spatial interpolation methods. Recent advances in remote sensing and machine learning approaches for salinity assessment were additionally considered during spatial interpolation and geoecological risk evaluation procedures (Wang et al., 2024).

Atmospheric aerosol load, soil salinity intensity, and hydrochemical mineralization indicators were integrated into a unified Geoecological Impact Index (GEI):

$$GEI = w_1A + w_2S + w_3W$$

where: A – atmospheric aerosol index; S – soil salinity index; W – water mineralization index; w_1, w_2, w_3 – weighting coefficients.

Weighting coefficients were determined using expert-based comparative assessment considering the relative environmental significance of atmospheric, pedospheric, and hydrospheric impacts under arid conditions. Weighting coefficients were validated through comparative sensitivity testing to minimize subjectivity and evaluate model stability under varying weighting scenarios.

Based on GEI values, the study area was classified into:

- high-risk zones;
- moderate-risk zones;
- low-risk zones.

2.7. Statistical Analysis

Statistical analysis was performed to evaluate the strength, significance, and spatial regularity of relationships among atmospheric aerosol load, soil salinization intensity, and hydrochemical transformation indicators within the potash industrial region under arid climatic conditions.

Descriptive statistical methods were applied to determine the mean, standard deviation, minimum, maximum, and coefficient of variation for $PM_{2.5}$, PM_{10} , electrical conductivity (ECe), total dissolved solids (TDS), Na^+ , Cl^- , and SO_4^{2-} concentrations. Prior to statistical analysis, data distribution characteristics were evaluated using the Shapiro–Wilk normality test.

Relationships among geoecological variables were assessed using Pearson correlation analysis for normally distributed datasets. Correlation coefficients (r) were interpreted according to standard statistical classification criteria, while statistical significance was evaluated at confidence levels of $p < 0.05$ and $p < 0.01$.

To evaluate spatial attenuation patterns of technogenic impacts, regression analysis was performed between geoecological indicators and distance from technogenic emission sources. Linear and exponential regression models were comparatively tested, and the model demonstrating the highest coefficient of determination (R^2) and lowest residual error was selected as the optimal representation of spatial geoecological trends.

Model performance was evaluated using:

- coefficient of determination (R^2);
- root mean square error (RMSE);
- residual distribution analysis.

To reduce potential multicollinearity effects among hydrochemical variables, pairwise correlation matrices were additionally examined prior to integrated geoecological assessment.

Spatial statistical analysis and interpolation procedures were conducted within the GIS environment using inverse distance weighting (IDW) interpolation to evaluate spatial gradients of atmospheric pollution, soil salinization, and hydrochemical mineralization.

Integrated geoecological risk zoning was performed using normalized Geoecological Impact Index (GEI) values. Index normalization was carried out using min–max standardization:

$$X_n = \frac{X - X_{min}}{X_{max} - X_{min}}$$

where: X_n – normalized indicator value; X – observed parameter value; X_{min} and X_{max} – minimum and maximum observed values.

The weighting coefficients used in GEI calculation were additionally evaluated through sensitivity analysis to assess the stability of spatial risk classification under varying weighting scenarios.

All statistical analyses were performed at a 95% confidence level using standard statistical and GIS-based analytical procedures commonly applied in environmental and geoecological investigations. The statistical framework incorporated seven principal monitoring points distributed along the dominant wind direction.

3. Results

3.1. Production Dynamics and Technogenic Load

Potassium chloride production is characterized as a highly resource-intensive technogenic system. During the processing of sylvinite ores, large volumes of rock mass are extracted, while a substantial proportion of the material is discharged into the environment as halite and insoluble mineral waste. Therefore, assessment of industrial activity requires not only evaluation of final KCl production volumes, but also comprehensive analysis of waste generation dynamics and associated technogenic pressure.

Production indicators of the Dehqonobod Potash Plant during 2020–2025 demonstrated a stable growth trend (Table 1). During this period, KCl production increased from 327 thousand tons to 450 thousand tons, while ore extraction volumes increased from 1.21 million tons to 1.60 million tons. In total, approximately 8.85 million tons of ore mass were extracted, resulting in the production of 2.41 million tons of KCl and the accumulation of 6.44 million tons of technogenic waste.

Table 1. Ore extraction, KCl production, and waste generation dynamics in the Dehqonobod potash industrial region during 2020–2025

Year	Ore extraction (million t)	KCl production (thousand t)	Waste generation volume (million t)
2020	1.21	327	0.883
2021	1.46	394	1.066
2022	1.59	430	1.160
2023	1.45	391.5	1.060
2024	1.54	416	1.124
2025	1.6	450	1.150
Total:	8.85	2408.5	6.443

Analysis showed that approximately 65–70% of the processed sylvinite mass was transformed into halite and associated mineral waste. Consequently, waste volumes increased from 0.883 million tons in 2020 to 1.150 million tons in 2025. The waste-to-ore ratio remained within 64.6–69.9%, confirming the high technogenic intensity of the production system.

The strong relationship between industrial production growth and waste accumulation indicates continuous expansion of halite waste dumps, which may intensify atmospheric saline aerosol migration and secondary salinization processes under arid climatic conditions. The dynamics of ore extraction, KCl production, and waste generation are presented in Figure 2.

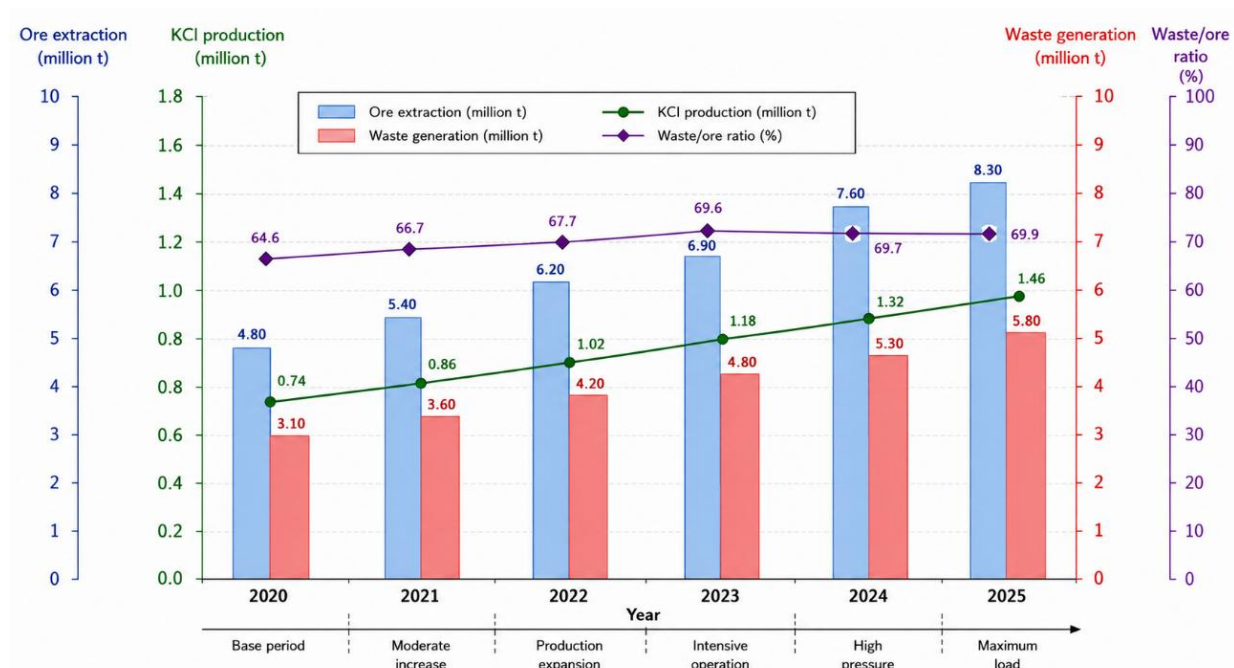


Fig. 2. Dynamics of ore extraction, KCl production, and waste generation in the Dehqonobod potash industrial region during 2020–2025.

Figure 2 demonstrates that increasing industrial production was accompanied by proportional growth in technogenic waste generation. In particular, the continuous accumulation of halite waste — the primary source of PM-related geoeological pressure — may intensify atmospheric aerosol loading and accelerate technogenic landscape transformation under arid environmental conditions. The obtained results indicate a direct functional relationship between production intensity and geoeological risk levels within the industrial region.

3.2. Atmospheric Migration of Saline Aerosols

Atmospheric monitoring results demonstrated the formation of elevated concentrations of saline aerosol particles in areas surrounding halite waste dumps and ore processing facilities. The spatial distribution of $PM_{2.5}$ and PM_{10} fractions was primarily controlled by wind direction, wind speed, and distance from technogenic sources. The exponential decrease in aerosol concentration with increasing distance from emission sources confirmed the intensive atmospheric migration of saline particles under arid environmental conditions (Shao & Dong, 2006; Shao, 2008; Xie et al., 2010; Duniway et al., 2019).

Due to limitations in long-term instrumental monitoring data, atmospheric aerosol loads were evaluated using scenario-based dispersion modeling calibrated to arid and windy environmental conditions. This approach enabled assessment of potential spatial gradients of aerosol concentration and the intensity of technogenic atmospheric impacts surrounding halite waste storage areas (Table 2).

Table 2. Scenario-based modeled atmospheric aerosol load around halite waste dumps under arid and windy climatic conditions

Point	Distance, km	PM _{2.5} , µg/m ³	PM ₁₀ , µg/m ³	Wind speed, m/s	Risk level
A1	0.5	48	185	6.5	High
A2	1.0	39	150	6.2	High
A3	2.0	30	112	5.8	High-moderate
A4	3.0	23	82	5.5	Moderate
A5	5.0	16	55	4.8	Moderate-low
A6	7.5	11	36	4.3	Low
A7	10.0	8	25	4.0	Low/background

Table 2 demonstrates a gradual decrease in atmospheric aerosol concentration with increasing distance from halite waste dumps. The highest PM_{2.5} and PM₁₀ concentrations were recorded within 0.5–1 km of the waste storage zones, reflecting intensive wind erosion and atmospheric entrainment of fine saline particles. In particular, PM₁₀ concentration decreased from 185 µg/m³ at a distance of 0.5 km to 25 µg/m³ at 10 km from the emission source.

The analysis revealed that high-risk atmospheric impact zones were mainly concentrated within a 0–3 km radius surrounding halite waste dumps. Moderate aerosol loading was observed within the 3–5 km zone, whereas concentrations beyond 5 km gradually approached background environmental levels. These findings confirm that wind erosion and atmospheric transport of technogenic saline particles represent major drivers of geoeological risk formation under arid climatic conditions.

To evaluate the spatial mechanisms of saline aerosol migration, a conceptual dispersion model incorporating wind direction, distance, and dry deposition processes was developed (Figure 3).

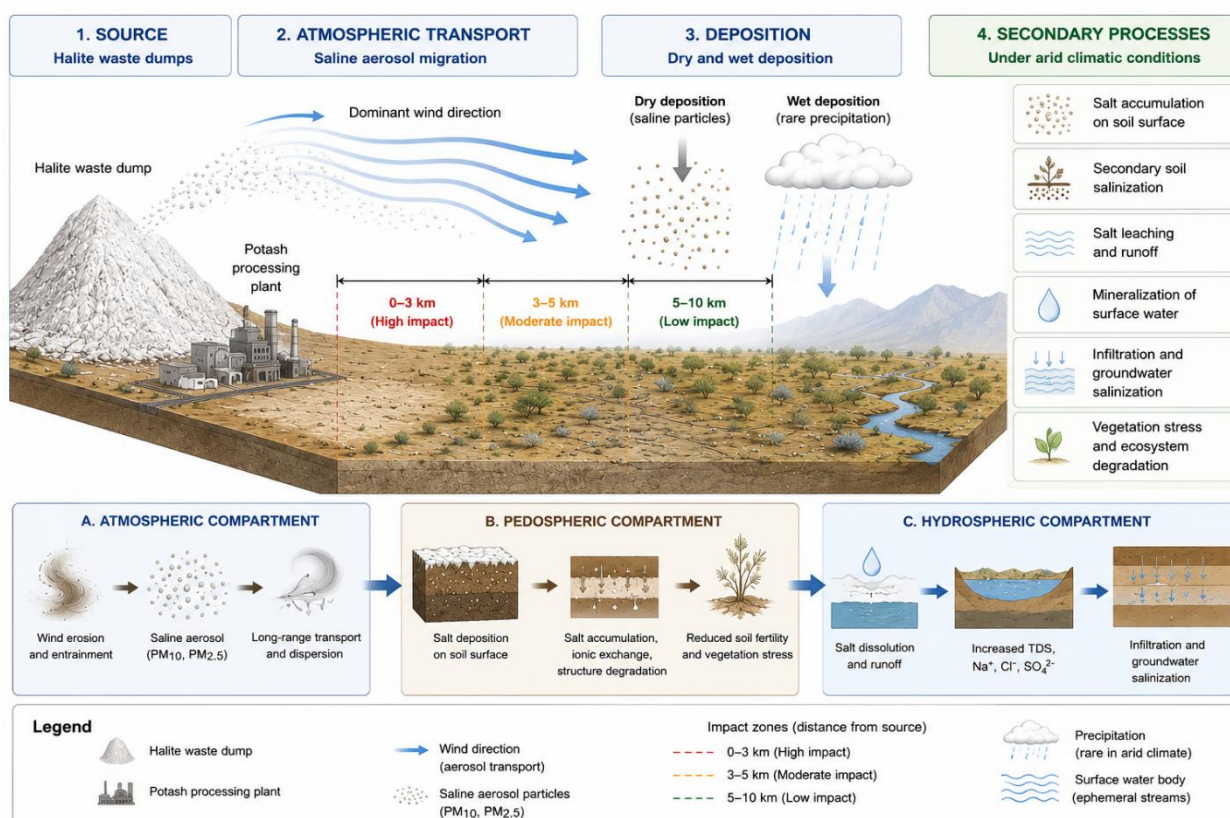


Fig. 3. Integrated pathways of saline aerosol transport and geoecological transformation under arid climatic conditions.

Figure 3 illustrates that aerosol concentration decreases exponentially with increasing distance along the dominant wind direction. The highest impact zone was concentrated within a 0–3 km radius surrounding the waste storage facilities, where atmospheric aerosol loading and soil salinity intensity reached maximum values.

Within the 3–5 km zone, aerosol dispersion exhibited a more diffuse spatial pattern accompanied by moderate geoecological impacts. At distances of 5–10 km, aerosol concentrations decreased substantially, while dry deposition processes became dominant. The obtained results indicate that halite waste dumps function as long-term atmospheric sources of saline aerosols under arid climatic conditions, and that atmospheric saline aerosol migration represents one of the principal mechanisms driving secondary salinization and technogenic geoecological transformation.

3.3. Secondary Soil Salinization Processes

Geoecological analysis of soil conditions revealed intensive development of secondary salinization processes in areas adjacent to technogenic facilities. Elevated electrical conductivity (ECe) values and increased concentrations of Na⁺ and Cl⁻ ions indicated strong influence from halite waste accumulation zones. Under arid climatic conditions, high evaporation rates and limited natural leaching processes promote long-term retention of technogenic salts within the soil environment (Sparks, 2003; FAO, 2008). Similar mechanisms of progressive salt accumulation and limited natural desalinization under arid environments were highlighted by Shokri (2024).

To evaluate the spatial distribution of soil salinization, ECe values obtained from monitoring points were analyzed and secondary salinization zones were delineated using GIS-based spatial interpolation techniques (Figure 4).

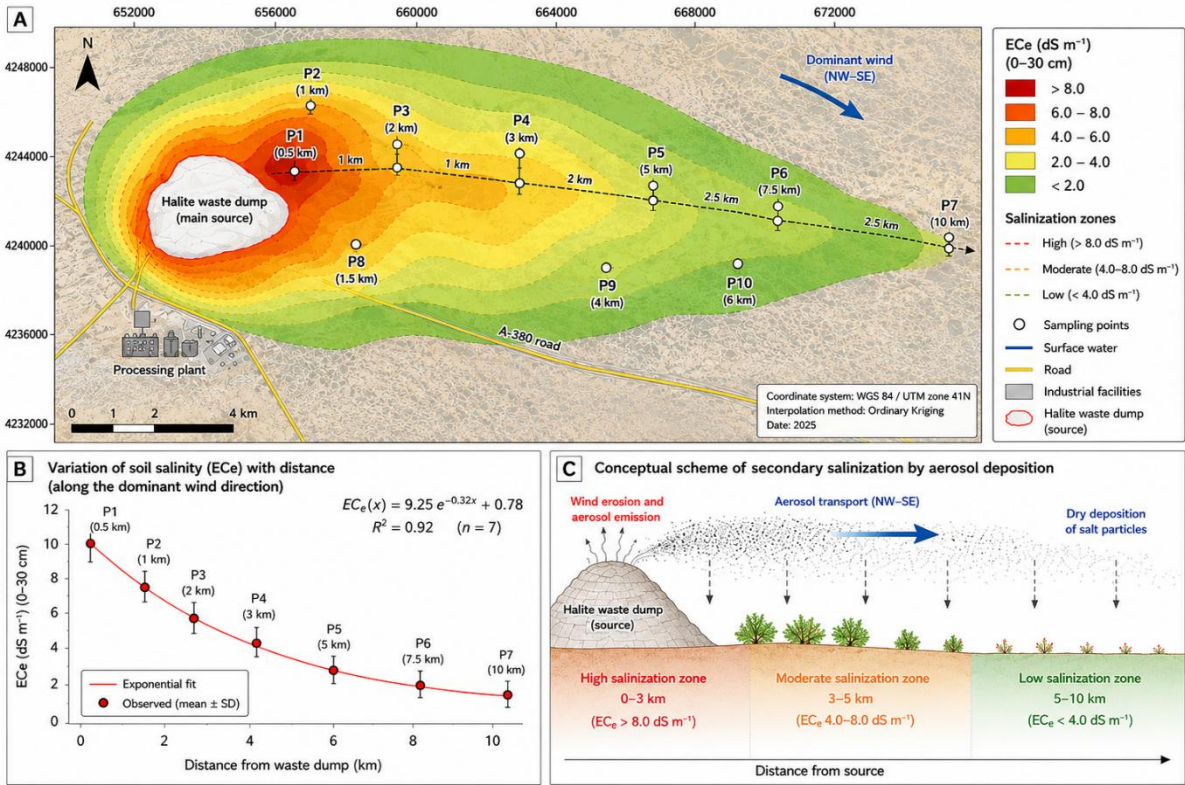


Fig. 4. Spatial distribution of secondary soil salinization around halite waste dumps under arid climatic conditions.

Figure 4 demonstrates the formation of a distinct spatial salinity gradient surrounding halite waste dumps. The highest salinity levels were identified in areas located near waste storage zones, where ECe values exceeded 8 dS/m. These territories were classified as high geoeological risk zones.

An exponential decrease in soil salinity intensity with increasing distance from technogenic sources was observed. Moderate salinity conditions were identified within the 3–5 km zone, whereas ECe values decreased substantially within the 5–10 km zone, approaching relatively stable background soil conditions. Regression analysis revealed a strong inverse relationship between soil salinity intensity and distance from emission sources ($R^2 = 0.92$).

Spatial analysis indicated that dry deposition of saline aerosol particles along the dominant wind direction resulted in the formation of spatially differentiated salinization zones. In particular, monitoring points located along the central axis of the aerosol plume exhibited elevated ECe values, confirming the dominant role of atmospheric salt transport in pedospheric transformation processes.

The obtained results demonstrate that under arid climatic conditions, halite waste dumps represent major drivers of pedospheric degradation and reduction of biological productivity. Furthermore, GIS-based identification of

salinization zones provides an effective tool for optimizing geoeological monitoring systems, planning reclamation strategies, and forecasting environmental risk levels within technogenically transformed landscapes.

3.4. Hydrogeoecological Transformations

Hydrogeoecological analysis demonstrated that mineralization processes affecting surface and groundwater systems in areas surrounding potash industrial facilities were strongly associated with technogenic salt migration. Elevated total dissolved solids (TDS) and electrical conductivity (EC) values were particularly pronounced in areas adjacent to halite waste dumps and sludge storage facilities. Under arid climatic conditions, high evaporation rates and limited water exchange processes intensify the accumulation of technogenic salts within hydrospheric systems (Kostecki & Ignatiuk, 2012; Alloway, 2013).

Due to limitations in long-term hydrogeochemical monitoring data, a scenario-based hydrochemical assessment model was applied to evaluate potential mineralization levels in surface and groundwater systems. The modeled data enabled assessment of spatial patterns of technogenic salt migration within the hydrosphere (Table 3).

Table 3. Scenario-based hydrochemical characteristics surrounding potash industrial facilities under arid climatic conditions

Point	Distance, km	TDS (mg/L)	EC (dS/m)	Na ⁺ (mg/L)	Cl ⁻ (mg/L)	SO ₄ ²⁻ (mg/L)	Water quality
W1	0.5	6200	8.9	1850	3100	420	Highly mineralized
W2	1.0	5400	7.8	1600	2700	395	Highly mineralized
W3	2.0	4300	6.5	1320	2150	360	Mineralized
W4	3.0	3200	5.1	980	1580	310	Moderate
W5	5.0	2200	3.9	710	1020	250	Moderate-low
W6	7.5	1450	2.8	430	690	190	Low
W7	10.0	980	1.9	260	420	140	Background

Table 3 indicates that the highest levels of water mineralization were concentrated in areas located near halite waste dumps. Maximum TDS and EC values were recorded within the 0.5–1 km zone surrounding waste storage areas, reflecting intensive migration of technogenic salts into hydrospheric systems. In particular, TDS values decreased from 6200 mg/L at a distance of 0.5 km to 980 mg/L at 10 km from the technogenic source.

Elevated Na⁺ and Cl⁻ concentrations confirmed that halite waste represents the primary source of hydrochemical mineralization. The gradual decrease in ion concentrations with increasing distance demonstrated the spatially differentiated nature of hydrogeochemical impacts within the study area.

The obtained results indicate that under arid climatic conditions, high evaporation intensity and restricted water exchange significantly enhance the accumulation of technogenic salts in surface and groundwater systems. Consequently, hydrogeochemical transformation processes represent one of the major geocological factors controlling environmental degradation and deterioration of regional water quality.

The identified hydrochemical gradients further confirm the integrated relationship between atmospheric aerosol transport, soil salinization, and hydrospheric mineralization processes within technogenically transformed arid landscapes (UNEP, 2021).

3.5. Integrated Geocological Risk Assessment and GIS-Based Zoning

Comprehensive geocological analysis demonstrated that transformations affecting atmospheric, pedospheric, and hydrospheric systems developed as interconnected processes under the influence of potash industrial activities. The spatial consistency of aerosol migration, soil salinization, and hydrochemical mineralization confirmed the formation of an integrated technogenic geocological system within the study area.

The Geoecological Impact Index (GEI) was calculated using atmospheric aerosol load, soil salinity intensity, and hydrogeochemical indicators. GIS-based interpolation and spatial overlay analysis enabled the delineation of high-, moderate-, and low-risk geocological zones within the industrial region (Figure 5).

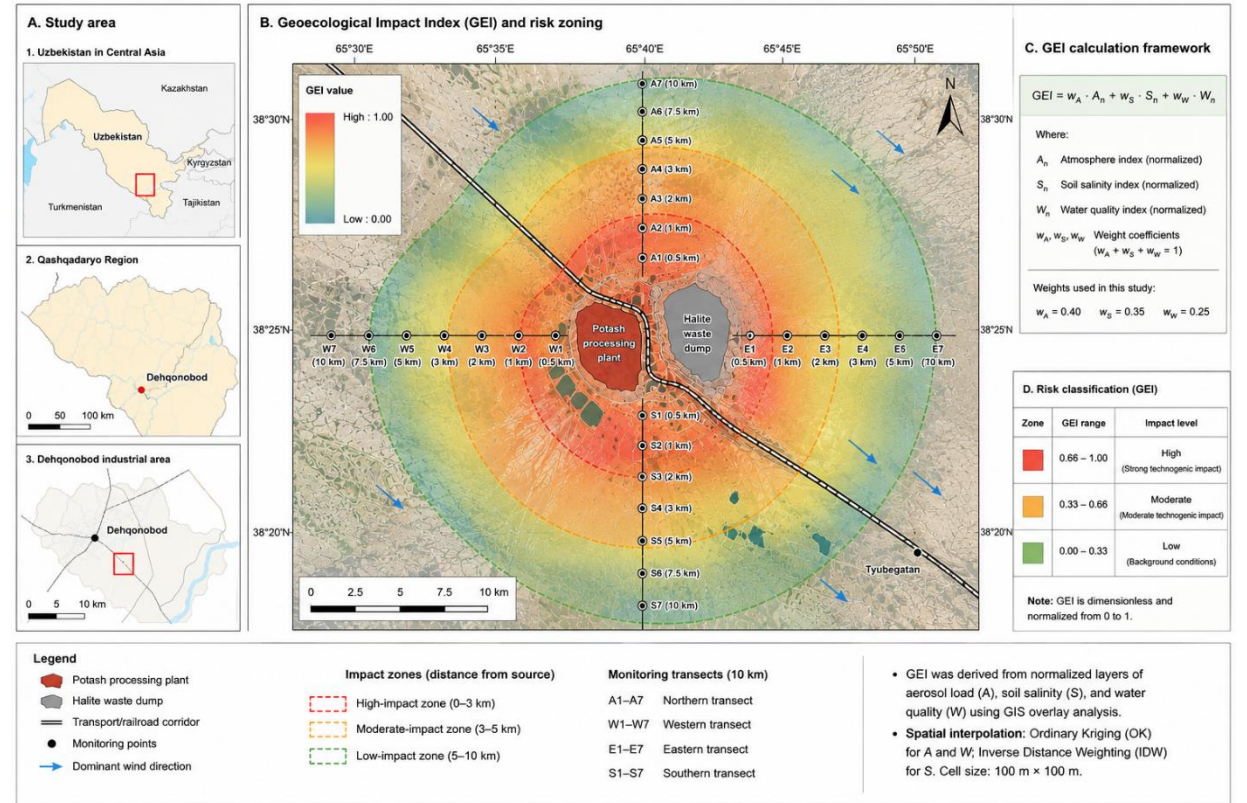


Fig. 5. GIS-based spatial distribution of the Geoecological Impact Index (GEI) and integrated geocological risk zoning of the Dehqonobod potash industrial region.

Figure 5 demonstrates that high geoecological risk zones were primarily concentrated within a 0–3 km radius surrounding halite waste dumps, processing complexes, and associated technogenic infrastructure. These areas were characterized by maximum atmospheric aerosol loads, elevated soil salinity levels, and increased hydrochemical mineralization.

Moderate-risk zones were identified within the 3–5 km zone, where aerosol dispersion intensity and salt migration processes gradually decreased. Beyond 5 km, geoecological indicators approached relatively stable background environmental conditions.

Spatial analysis revealed that the intensity of technogenic impacts was highest along the dominant wind direction. Areas located along the central axis of the aerosol plume exhibited pronounced soil salinization and hydrochemical transformation processes, confirming that atmospheric saline aerosol transport represents one of the principal mechanisms driving geoecological transformation under arid environmental conditions.

To evaluate the functional relationships among atmospheric aerosol load, soil salinity intensity, and hydrochemical indicators, correlation analysis was performed (Table 4).

Table 4. Correlation matrix between atmospheric aerosol load, soil salinity, and hydrochemical indicators.

Parameter	PM ₁₀	ECe	TDS	Na ⁺	Cl ⁻
PM ₁₀	1.00	0.94	0.88	0.91	0.93
ECe	0.94	1.00	0.86	0.89	0.92
TDS	0.88	0.86	1.00	0.95	0.97
Na ⁺	0.91	0.89	0.95	1.00	0.96
Cl ⁻	0.93	0.92	0.97	0.96	1.00

Statistical Significance Analysis

To evaluate the reliability of the identified relationships among atmospheric aerosol load, soil salinity, and hydrochemical indicators, statistical significance analysis was performed using Pearson correlation coefficients and regression analysis. The obtained results demonstrated statistically significant positive relationships among the analyzed geoecological parameters at the 95% confidence level ($p < 0.05$).

The strongest statistically significant relationship was identified between PM₁₀ concentration and soil electrical conductivity (ECe) ($r = 0.94$, $p < 0.01$), confirming that atmospheric transport of saline aerosol particles represents one of the dominant drivers of secondary soil salinization within the study area. Similarly, strong positive correlations were observed between TDS and Cl⁻ concentrations ($r = 0.97$, $p < 0.01$), indicating that halite waste dumps function as the principal source of hydrochemical mineralization processes.

Regression analysis further demonstrated a statistically significant inverse relationship between soil salinity intensity and distance from technogenic emission sources ($R^2=0.92$, $p<0.01$). These results confirm the spatial regularity and non-random nature of technogenic geoecological transformation processes under arid climatic conditions.

The statistical analysis supports the reliability of the proposed GIS-based geoecological monitoring framework and confirms the integrated relationships among atmospheric, pedospheric, and hydrospheric transformation processes within technogenically disturbed arid industrial landscapes.

The obtained results demonstrate that GIS-based integrated geoecological monitoring provides an effective framework for environmental risk forecasting, spatial optimization of reclamation measures, and sustainable management of potash industrial facilities under arid climatic conditions.

4. Discussion

The obtained results confirmed that halite waste dumps and potash industrial facilities under arid climatic conditions exert complex technogenic impacts on atmospheric, pedospheric, and hydrospheric systems. One of the principal patterns identified in this study was the exponential decrease in aerosol concentration with increasing distance from technogenic emission sources. This finding is consistent with fundamental studies on wind erosion and aerosol transport processes, which demonstrate that fine saline particles can undergo intensive atmospheric migration in arid environments (Shao, 2008; Goudie & Middleton, 2006).

Elevated aerosol concentrations in areas adjacent to waste storage facilities intensify dry deposition processes and contribute to the development of secondary soil salinization. The high EC_e values and increased Na^+ and Cl^- concentrations identified during the study indicate that atmospheric salt transport represents one of the dominant mechanisms driving pedospheric degradation. These results are consistent with previous studies demonstrating that aeolian transport of saline particles can significantly alter the physicochemical properties of soils in arid and semi-arid environments (Xie et al., 2010; Ravi et al., 2010). Similar relationships between soil texture, wind erosion intensity, and dust emission dynamics in dryland environments were discussed by Webb et al. (2020).

Regression analysis revealed a strong functional relationship between aerosol concentration and soil salinity intensity ($R^2 = 0.92$), indicating that halite waste dumps generate localized but highly intensive geoecological transformation processes. Similar spatial patterns have been reported in potash industrial regions of Canada and Belarus, where saline aerosol dispersion was found to be concentrated within several kilometers of technogenic sources (Kostecki & Ignatiuk, 2012). However, most previous studies were conducted under humid climatic conditions, where infiltration and natural leaching processes play a more significant role in controlling salt migration.

In contrast, under arid climatic conditions, high evaporation rates and restricted water exchange promote long-term accumulation of technogenic salts within atmospheric, soil, and hydrological systems. Previous studies also demonstrated that wastewater and brine generated during potash ore enrichment may significantly intensify hydrochemical transformation and environmental salinization processes in mining regions (Glushankova et al., 2023). This contributes to increased spatial persistence of geoecological risks in dryland industrial environments. In particular, highly mineralized zones surrounding halite waste dumps may significantly affect both surface and groundwater quality. Elevated TDS and EC values identified in this study confirm active migration of technogenic salts into hydrospheric systems, which is consistent with previous investigations of anthropogenic salinization processes (Kostecki & Ignatiuk, 2012; Alloway, 2013). Similar groundwater salinization and technogenic salt migration processes were identified in the Verkhnekamskoe potash deposit, where highly mineralized drainage waters significantly affected surrounding hydrogeochemical systems (Khayrulina & Maksimovich, 2018). Comparable hydrogeochemical and pedospheric transformation processes associated with potash waste storage were identified in the Verkhnekamskoe potash mining region (Mitrakova & Khayrulina, 2019).

One of the major scientific contributions of this study is the development of an integrated geoecological risk assessment framework based on GIS technologies and the Geoecological Impact Index (GEI). Spatial overlay and interpolation analyses demonstrated strong spatial relationships among atmospheric aerosol load, soil salinization intensity, and hydrochemical mineralization. These findings confirm that geoecological transformations within potash industrial landscapes should be considered as interconnected technogenic–landscape systems rather than isolated environmental processes. Similar integrated geoecological transformation patterns were also reported for the Verkhnekamskoe potash mining region, where atmospheric pollution, soil degradation, and hydrospheric mineralization were identified as interconnected environmental processes (Ushakova et al., 2023).

Previous international studies have mainly applied GIS approaches to hydrogeochemical monitoring or assessment of soil degradation processes. In contrast, the present study integrates atmospheric, pedospheric, and hydrospheric indicators within a unified geoecological assessment framework. This integrated approach represents an important methodological advancement for environmental risk assessment of potash industrial facilities under arid climatic conditions. Recent studies also emphasize the increasing importance of GIS-based integrated salinity assessment and spatial environmental modeling for water-scarce industrial regions.

The results further indicate that reclamation strategies for halite waste dumps in arid environments should avoid excessive water-based suppression methods. Due to the high solubility of halite, intensive wetting may increase the formation of highly mineralized leachates and intensify hydrospheric contamination. Therefore, integrated reclamation approaches based on mechanical stabilization, surface isolation, and halophytic vegetation establishment

appear to be more effective for arid industrial landscapes. Such approaches may reduce wind erosion intensity, limit atmospheric aerosol emissions, and gradually stabilize technogenic landscapes (Shao, 2008; Ravi et al., 2010).

Despite the strong spatial and statistical relationships identified in this study, several limitations should be acknowledged. Due to limited long-term instrumental monitoring data, part of the atmospheric aerosol and hydrochemical datasets was generated using scenario-based environmental modeling calibrated to regional arid climatic conditions. Consequently, future studies should incorporate continuous field-based monitoring, remote sensing validation, and long-term hydrogeochemical observations to improve the accuracy of geoecological risk assessment models.

Overall, the obtained results demonstrate that geoecological impacts associated with potash industrial facilities under arid climatic conditions represent complex, spatially differentiated, and interconnected environmental transformation systems. The proposed integrated monitoring and risk assessment framework may serve as a universal methodological model for geoecological assessment and sustainable environmental management of mining and chemical industrial regions located within arid and semi-arid environments.

5. Conclusion

The obtained results demonstrated that geoecological processes developing within potash industrial regions under arid climatic conditions are characterized by interconnected technogenic transformations affecting atmospheric, hydrospheric, pedospheric, and biological systems. Mining, ore processing, transportation, and halite waste storage activities were identified as major factors contributing to environmental risk formation in arid industrial landscapes.

The study confirmed that intensive wind activity and high evaporation rates under arid climatic conditions promote atmospheric migration of saline aerosol particles and accelerate secondary salinization processes. Halite waste dumps and saline tailings were identified as long-term technogenic sources affecting soil properties, hydrochemical regimes, and biological productivity through atmospheric aerosol transport and dry deposition mechanisms (Shao, 2008; Xie et al., 2010).

Spatial analysis revealed that the highest geoecological impact intensity was concentrated around halite waste dumps, processing facilities, and transportation infrastructure. GIS-based assessment enabled the delineation of high-, moderate-, and low-risk geoecological zones within the industrial region. Strong positive correlations among atmospheric aerosol concentration, soil salinity intensity, and hydrochemical mineralization confirmed the integrated nature of geoecological transformation processes within technogenically disturbed arid landscapes (Alloway, 2013).

Hydrogeoecological analysis demonstrated that restricted water exchange and high evaporation intensity significantly enhance the accumulation of technogenic salts in surface and groundwater systems under arid

environmental conditions. Elevated electrical conductivity values and increased Na⁺ and Cl⁻ concentrations confirmed the intensive development of secondary salinization processes within the study area (Sparks, 2003; FAO, 2008).

Based on the obtained results, an integrated geoecological monitoring and environmental risk assessment framework was developed for potash industrial facilities located in arid climatic regions. The proposed approach enables comprehensive evaluation of technogenic transformations affecting atmospheric, hydrospheric, pedospheric, and biological environments, while also providing a scientific basis for geoecological risk forecasting and environmental sustainability management.

The proposed monitoring system may serve as an effective scientific and practical tool for environmental risk management, reclamation planning, and mitigation of technogenic impacts in potash industrial regions. Furthermore, the developed framework may be applied as a universal geoecological assessment model for mining and chemical industrial facilities located within arid and semi-arid climatic environments. The developed framework may also support future integration of remote sensing technologies and GIS-based environmental forecasting systems for sustainable management of arid industrial landscapes. The obtained results may support the development of environmentally sustainable waste-management strategies and geoecological regulation policies for potash industrial regions located within arid and semi-arid climatic zones.

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Declarations

Acknowledgements This is not applicable

Funding This is not applicable

Authors' Contributions T. Yarboboiev supervised the research and contributed to the study design and manuscript revision; Y. Nurboboiev carried out the main research work, performed GIS and statistical analysis, and prepared the manuscript; K. Kosimova participated in data collection, literature review, and environmental analysis; Z. Uzokov contributed to data interpretation, environmental modeling, and editing of the manuscript. All authors reviewed, discussed, and approved the final version of the manuscript.

Ethical Approval This is not applicable

Consent to Participate This is not applicable

Consent to Publish All authors are aware and agreed to submit the paper, which is original and unpublished, and agreed to grant the copyright (or publishing license) to the journal.

Competing Interests The authors declare no competing interests.

Data Availability Statement All data generated or analyzed during this study are included in this article