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HYDRO-MINERAL RESOURCES OF THE ALAKOL BASIN AS A DRIVER OF HEALTH AND WELLNESS TOURISM DEVELOPMENT: A GEOECOLOGICAL PERSPECTIVE

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Abstract: This paper provides a comprehensive geoecological evaluation of the hydro-mineral resources of the Alakol Basin, interpreted within the framework of sustainable health and wellness tourism development. The lacustrine system, situated in the arid zone of south-eastern Kazakhstan, represents a closed hydrological basin distinguished by comparatively high mineralization, the occurrence of peloid deposits, and marked spatial variability of its hydrochemical regime. The principal objective of the study is to determine the chemical, microbiological, and radiological characteristics of surface waters and bottom sediments within the Alakol Basin, and to assess the implications of recreational pressure for the geoecological stability of the adjacent coastal landscapes. Field surveys undertaken in 2024–2025 involved the collection of 140 samples of water and sediments. Laboratory investigations included macro- and microelement analysis using scanning electron microscopy coupled with energy-dispersive spectroscopy, alongside microbiological and radiological testing conducted in accordance with national sanitary regulations. Statistical data on visitor numbers were further employed to estimate recreational load intensity. The findings reveal moderate to elevated mineralization and the presence of biologically significant elements (Mg, Ca, Na, K, Fe, Ba, Zn, Cu, Cr, and Ni), while concentrations of potentially hazardous metals remain below permissible thresholds. Radiological and microbiological indicators confirm sanitary suitability for recreational use. Nevertheless, excessive visitor pressure contributes to localized ecosystem degradation, underscoring the necessity of environmentally regulated tourism management within the basin.

Keywords: Alakol Basin; hydro-mineral resources; geoecological assessment; health and wellness tourism; tourism geography

1. Introduction

The Alakol Basin, located in the Zhetysu and Abai regions of Kazakhstan, is a closed lacustrine system of the arid zone of Central Asia comprising Zhalanashkol, Alakol, and Sasykkol Lakes.

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The basin is characterized by a sharply continental climate, restricted water exchange, high surface-water mineralization, and extensive coastal peloid deposits (Jetimov et al., 2025; Utepbayeva & Mukatai, 2018). Its endorheic hydrological regime and limited water circulation make the ecosystem particularly vulnerable to anthropogenic impacts.

Saline and slightly mineralized lakes are internationally recognized as valuable natural resources that combine ecological, balneological, and recreational functions. Their sustainable use depends on balancing the exploitation of therapeutic resources with the preservation of geoeological integrity (Calin et al., 2019; Gheorghievici et al., 2023). Previous studies have shown that excessive recreational pressure and climate-driven evaporation may alter hydrochemical regimes and reduce the therapeutic quality of peloids (Pozo et al., 2010). European research has also highlighted the importance of ecological carrying capacity and visitor management, particularly in closed or weakly flushed lake systems (Dunets et al., 2020).

Although the Alakol Basin shares many characteristics with saline lakes of Eastern and Southern Europe, it is distinguished by a more continental climate, pronounced seasonal water-level fluctuations, and a hydrological balance controlled by river inflow and intensive evaporation (Boros & Kolpakova, 2018). Previous investigations have described the hydrochemical characteristics of the Alakol depression (Amirgaliev et al., 2003; Mukayev et al., 2024), but have not examined the basin as an integrated geoeological system under increasing recreational pressure.

Despite the existing hydrochemical and tourism-related studies, no comprehensive assessment has simultaneously considered spatial hydrochemical variability, sanitary, microbiological and radiological conditions, and recreational load within the ecological carrying-capacity framework. This gap limits the development of scientifically based strategies for sustainable health and wellness tourism.

Therefore, the aim of this study is to provide a comprehensive geoeological and balneological assessment of the hydro-mineral resources of the Alakol Basin and to evaluate their ecological stability under the increasing recreational pressure. Specifically, the study examines (i) the spatial variability of hydrochemical characteristics, (ii) the compliance of sanitary, microbiological, and radiological indicators with national safety standards, and (iii) the extent to which current recreational use exceeds the ecological carrying capacity of the basin.

The study is based on the concept of ecological carrying capacity in endorheic lake systems and applies an integrated methodology combining seasonal hydrochemical sampling, microbiological and radiological monitoring, heavy-metal analysis of bottom sediments, and the calculation of an Integrated Environmental Index (IEI) together with recreational density. The results provide a scientific basis for regulating visitor pressure, improving environmental management, and supporting the sustainable development of health and wellness tourism in the Alakol Basin.

2. Literature review

Saline and slightly mineralized lakes in arid and semi-arid regions are important objects of geographical and geoeological research because of their endorheic hydrological regime, high mineralization, and unique biogeochemical processes responsible for the formation of therapeutic peloids (Hammer, 1986; Williams, 2002). Their restricted water exchange limits self-purification capacity and increases vulnerability to climatic variability and anthropogenic impacts.

International studies consider saline lakes not only as valuable natural ecosystems but also as important resources for health and wellness tourism. Research conducted in Europe demonstrates that sustainable management depends on balancing the utilization of hydro-mineral resources with the preservation of geoecological integrity (Calin et al., 2019; Carretero et al., 2010). Particular attention has been given to hydrochemical composition, radioecological safety, and the ecological carrying capacity of recreational areas, since excessive tourist pressure may degrade water quality, vegetation, and therapeutic mud resources (Coccossis & Mexa, 2004; Gössling et al., 2015; Pessot et al., 2021).

Previous studies have also demonstrated that climatic variability, evaporation, and river regulation substantially influence the hydrochemical balance of endorheic lakes (Williams, 2002; Wurtsbaugh et al., 2017). Consequently, integrated hydrochemical, geochemical, microbiological, and radiological assessments are regarded as essential for evaluating the suitability of hydro-mineral resources for recreational and therapeutic use (Carretero et al., 2010; Hall, 2004).

In Kazakhstan, research has mainly focused on the hydrochemical characteristics of the Alakol depression, spatial variability of lake waters, and the tourism potential of the region (Dostay & Tolganbayeva, 1997; Erdauletov, 2012; Valeev et al., 2019). More recent studies have examined water quality (Mukayev et al., 2024), hydro-mineral recreational resources (Jetimov et al., 2025), microbiological characteristics of therapeutic muds (Dzhetimov et al., 2014), and recreational development (Valeyev et al., 2024). However, these investigations have addressed individual aspects of the lake system rather than provided an integrated assessment.

Consequently, comprehensive studies that combine hydrochemical composition, microbiological and radiological safety, bottom-sediment geochemistry, and recreational pressure within an ecological carrying-capacity framework remain lacking for the Alakol Basin. Addressing this research gap, the present study provides an integrated geoecological assessment of the Zhalanashkol–Alakol–Sasykkol lake system to support the sustainable development of health and wellness tourism.

3. Methodology

3.1. Research area

The Alakol Basin is located in the Zhetysu and Abai regions of Kazakhstan and represents a closed lacustrine system in the arid zone of Central Asia. Alakol Lake occupies an intermontane depression between the Zhetysu Alatau and the Barlyk, Arasantau, and Argarly mountain ranges. The lake is fed by the Irgaity, Zhamanty, Emel, Kusak, Tasty, Arasan, and Shagantogay rivers, which originate in the surrounding mountains and are supplied mainly by snowmelt and glacier runoff (Aktymbayeva, 2006; Dostay & Tolganbayeva, 1997).

The lake extends between 45°43'46"–46°30'54" N and 81°20'24"–82°08'18" E, covering 2,696 km² with a water volume of 58.56 km³, a maximum depth of 54 m, and a mean depth of 22 m (Amirgaliev et al., 2003).

The spatial configuration of the study area is presented in Figure 1. Regional-scale mapping was based on MODIS satellite imagery (Terra/Aqua, 250 m spatial resolution) obtained from the National Aeronautics and Space Administration (NASA) Land Processes Distributed Active Archive Center (LP DAAC, NASA, n.d.). Detailed mapping of the study area was performed using Landsat-8 OLI/TIRS satellite imagery (Collection 2, Level-2 Science

Products; 30 m spatial resolution) accessed via the United States Geological Survey (USGS) EarthExplorer platform (USGS, n.d.). High-resolution imagery of the Koktuma recreational zone was acquired from Google Earth Pro (Google, n.d.). All spatial data were processed and visualized using ArcGIS 10.8 software (Esri Inc., 2023). Additional spatial data were obtained from SasPlanet imagery (SASGIS, n.d.) and unmanned aerial vehicle (UAV) surveys conducted in 2024–2025.

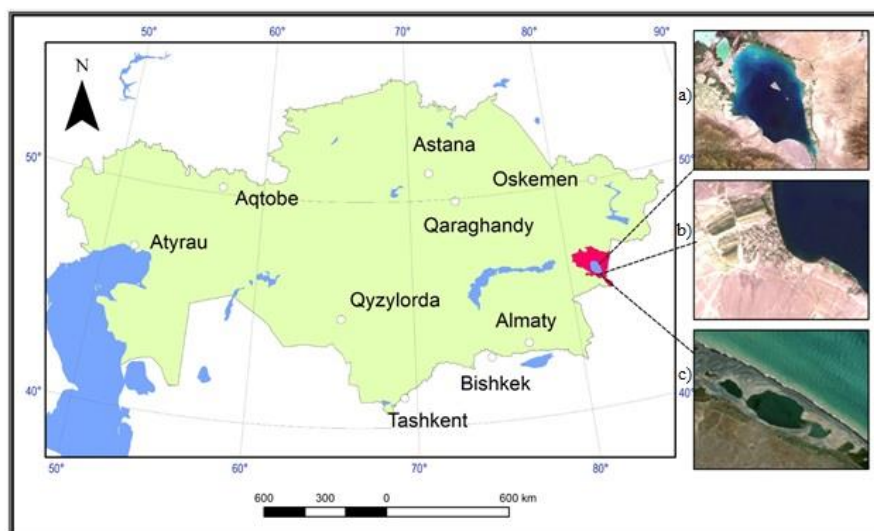


Figure 1. Geographical location of Alakol Lake within Kazakhstan.

Note. A: Regional location of the Alakol Basin in Kazakhstan, adapted from *LP DAAC Data Pool*, by NASA, n.d. (<https://lpdaac.usgs.gov/>), in the public domain. B: Satellite image of the Koktuma recreational zone, adapted from *EarthExplorer*, by USGS, n.d. (<https://earthexplorer.usgs.gov/> <https://lpdaac.usgs.gov/>), in the public domain. C: UAV image of the Koktuma recreational zone, adopted from *SAS.Planet: Satellite imagery and map viewer*, by SASGIS, n.d. (<https://www.sasgis.org/sasplaneta/>), in the public domain.

The Alakol Basin was selected because it represents a vulnerable endorheic hydro-mineral system experiencing rapid tourism development. Its mineralized waters and peloid deposits provide significant potential for health and wellness tourism while requiring environmentally sustainable management.

3.2. Research design and sampling procedure

The study employed an integrated ecological-geographical and hydrochemical approach adapted from limnological models for endorheic lakes (Plotnikov et al., 2021; Yapiyev et al., 2017). Unlike conventional models focusing primarily on climatic and hydrological controls, the present study incorporated recreational pressure as an additional driver of spatial hydrochemical variability.

The lake was divided into four sectors (northern, southern, western, and eastern). Field investigations were conducted during the peak and post-tourism seasons (April and October) in 2024–2025.

A total of 140 water, bottom-sediment, and therapeutic mud (peloid) samples were collected 3–5 m from the shoreline. Sampling locations were identified using satellite imagery and 1:50,000 topographic maps to ensure representative coverage of recreational and natural areas. Laboratory analyses were performed in accredited laboratories of the Department of Sanitary and Epidemiological Control of the Zhetysu Region.

The analytical program included determination of pH, total mineralization, total dissolved solids (TDS), major ions (Ca^{2+} , Mg^{2+} , Na^{+} , K^{+} , Cl^{-} , SO_4^{2-}), nitrogen compounds (NH_4^{+} , NO_2^{-} , NO_3^{-}), and heavy and trace metals in water, sediments, and peloids. Heavy metals were analyzed using scanning electron microscopy coupled with energy-dispersive spectroscopy (SEM-EDS; JEOL JSM-IT200, Japan). Microbiological analyses included the detection of lactose-positive coliform bacteria, coliphages, and helminth eggs. Radiological assessment was conducted by measuring alpha and beta activity levels (Ministry of Health of the Republic of Kazakhstan [RK], 2023; Standard of the Republic of Kazakhstan [ST RK] 3468-2019, 2019).

3.3. Spatial distribution of sampling sites

During field investigations conducted in 2024–2025, water, bottom sediment, and therapeutic mud samples were collected from the northern, southern, western, and eastern sectors of Alakol Lake (Figures 2).

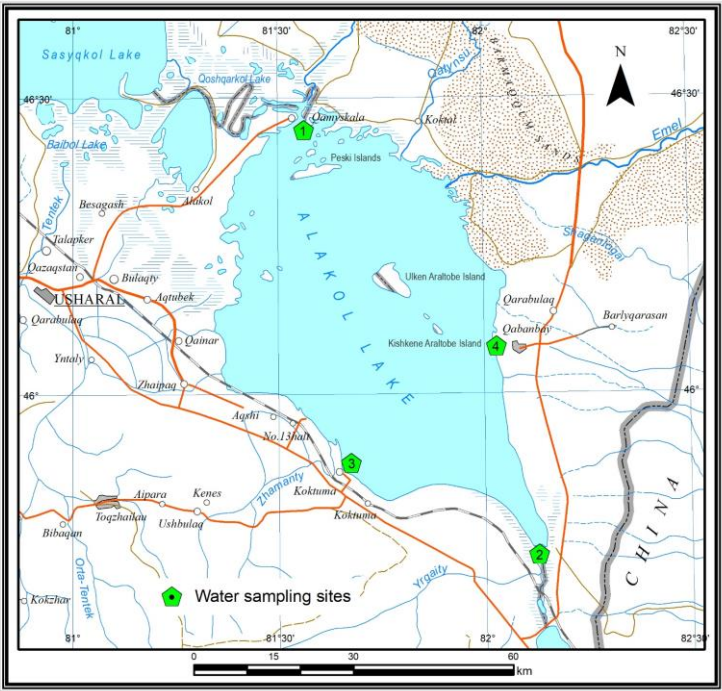


Figure 2. Map of sampling location.

Note: Author's compilation based on field surveys conducted in 2024–2025 using ArcGIS software (Esri Inc., 2023).

3.4. Data processing and analytical methods

Hydrochemical, microbiological, radiological, and sediment data were analyzed using descriptive statistics, comparative hydrochemical analysis, and regulatory sanitary assessment. Concentrations measured in the four lake sectors were compared with national water-quality standards and interpreted following approaches commonly applied to endorheic lake systems (Liu et al., 2025; Ren et al., 2022; Yapiyev et al., 2017).

Spatial variability was evaluated using minimum, maximum, and mean values together with the Percentage Difference Index (PDI):

$$PDI = \frac{|C_1 - C_2|}{\max(C_1, C_2)} \times 100\% \quad (1)$$

where C_1 and C_2 represent concentrations in two compared sectors.

Sanitary assessment was performed by comparing hydrochemical, microbiological, and radiological indicators with the regulatory standards of the Republic of Kazakhstan. Microbiological results were expressed as colony-forming units per liter (CFU/L), while radiological activity was measured in Bq/L.

Recreational pressure was estimated from official tourism statistics and calculated as visitor density (persons ha⁻¹), representing the ratio of daily tourist numbers to the recreational area. Statistical analysis and graphical visualization were performed using Microsoft Excel. The integrated methodological framework enabled assessment of hydrochemical conditions, environmental quality, and the recreational suitability of the Alakol Basin.

4. Results

4.1. Hydrochemical characteristics of lake water

Hydrochemical analysis indicates that the lake water is characterized by moderate mineralization and relatively stable concentrations of major cations, including Ca²⁺, Mg²⁺, Na⁺, and K⁺. The total mineralization ranges from 1,450 to 2,070 mg/dm³, reflecting spatial differentiation across the basin (Table 1). All analyzed concentrations of heavy and trace metals remained below the maximum permissible concentrations established by the sanitary regulations of the Republic of Kazakhstan (Ministry of Health of the RK 2023; ST RK 3468-2019, 2019).

Table 1. Chemical composition of Alakol Lake water samples (2025)

Name of indicators	Detected concentration (mg/dm ³)			Difference in chemical composition (%)	Detected concentration (mg/dm ³)		Difference in chemical composition (%)
	MPC (Standards)	Eastern part	Western part		Northern part	Southern part	
Cations							
B	0.5	0.0081	0.0055	< 32.09	0.0076	0.0059	< 22.36
Ca	130	0.1997	0.1303	< 34.75	0.96	0.85	< 11.45
Si	0.02	0.0027	0.0014	< 48.14	0.0034	0.0018	< 47.05
Mg	40	18.81	11.79	< 37.32	21.33	12.14	< 43.08

Table 1. Chemical composition of Alakol Lake water samples (2025) (*continued*)

Name of indicators	Detected concentration (mg/dm ³)			Difference in chemical composition (%)	Detected concentration (mg/dm ³)	Difference in chemical composition (%)	
	MPC (Standards)	Eastern part	Western part		Northern part	Southern part	
Cations							
K	20	0.0346	0.0134	< 61.27	0.0413	0.0322	< 22.03
Cu	1.0	0.06	0.032	< 46.66	0.55	0.50	< 9.09
Pb	0.03	0.0005	0.0001	< 80	-	-	-
Zn	1.0	0.4	0.41	> 2.43	0.44	0.41	> 6.81
Cr	0.05	0.002	0.032	> 37.5	0.020	0.019	> 5
Cd	0.001	0.0006	0.0005	< 16.66	-	-	-
Mn	1.0	0.05	0.41	> 87.8	-	0.42	-
Li	0.1	0.030	0.020	< 3.33	0.021	0.12	< 82.5
Sb	0.05	0.005	0.019	> 73.68	0.037	0.0024	< 93.51
Ba	0.1	0.003	0.03	> 90	0.062	0.024	< 61.29
Sr	7.0	1.28	1.55	> 17.41	3.20	3.23	> 13.04
Bi	0.1	0.005	0.033	> 84.84	0.058	0.041	< 29.31
Co	0.1	0.004	0.027	> 85.18	0.036	0.033	< 13.04
Na	200	11.37	17.40	> 34.65	99.4	85.17	< 14.31
As	0.05	0.006	0.02	> 70	-	-	-
Se	0.01	0.006	0.004	< 33.33	0.007	0.004	< 13.04
Ni	0.1	0.007	0.019	> 63.15	0.064	0.041	< 35.93
Al	0.5	0.008	0.32	> 97.5	0.41	0.34	> 17.07
Mo	0.25	0.004	0.11	> 96.36	0.18	0.12	< 33.33
Anions							
Cl ⁻	350	16.4	40.4	> 59.4	40.2	33.1	< 17.66
SO ₄ ²⁻	500	43.7	36.8	< 15.78	36.0	39.5	> 8.86
NH ₄ ⁺	2.0	0.05	0.08	> 37.5	0.08	0.08	-
NO ₂ ⁻	3.3	0.038	0.02	< 47.36	0.8	-	-
NO ₃ ⁻	45	2.9	1.43	< 50.68	3.2	2.0	< 37.5
COD	15–30	19.4	18.6	< 4.12	17.2	17.0	< 1.16
TDS	1000	519	352	< 32.17	506	340	< 32.8
pH	-	7.9	8.4	-	8.2	7.9	-
Total mineralization	-	2070	1450	< 29.95	1820	1567	< 13.9

Note. Laboratory test results of Alakol Lake water samples obtained in the accredited bacteriological laboratory of the Department of Sanitary and Epidemiological Control of the Zhetysu Region (2024–2025).

Spatial differences reflected hydrological conditions and the influence of groundwater and river inflow. The eastern sector showed elevated concentrations of B, Mg, K, Si, Ca, Cu, Se, SO₄²⁻, NO₂⁻, and NO₃⁻, whereas the northern shallow-water sector contained comparatively higher concentrations of B, Mg, K, Si, Ca, Li, Sb, Ba, Co, and Na, probably owing to reduced water exchange. The southern sector exhibited lower mineralization and lower heavy-metal concentrations under the influence of river inflow (Irgaity, Zhamanty, and Emel). In contrast, the western recreational sector showed increased concentrations of Zn, Mn, Sb, Ba, Sr, Co, Na, and Cl, indicating local anthropogenic influence. Despite these spatial differences, none of the analyzed parameters exceeded regulatory limits.

4.2. Bottom sediment composition

Laboratory analysis of bottom sediments revealed the presence of Pb, As, Cr, and Co; however, their concentrations remained below established maximum permissible levels (Table 2). The geochemical composition of sediments suggests that they may be considered a potential natural therapeutic resource, provided that recreational pressure remains controlled and secondary contamination is prevented.

Table 2. Heavy metal concentrations in bottom sediments of Alakol Lake (mg/kg)

Indicators	MPC (Standards)	Western part	Eastern part	Northern part	Southern part
Pb	32.0	0.015	0.004	0.19	0.05
As	2.0	0.004	0.008	0.005	0.007
Cr	6.0	0.007	0.003	0.007	0.004
Co	5.0	0.014	0.002	0.008	0.005

Note. Laboratory test results of Alakol Lake water samples obtained in the accredited bacteriological laboratory of the Department of Sanitary and Epidemiological Control of the Zhetysu Region (2024–2025).

4.3. Radiological and microbiological assessment

Radiological analysis of alpha and beta activity in water samples demonstrated low levels of natural radioactivity, fully compliant with national safety standards (Ministry of Health of the RK, 2023; ST RK 3468-2019, 2019, Table 3).

Table 3. Radioactivity indicators (α - and β -activity) of Alakol Lake water samples

Indicators	Standards (MPC)	Part of Alakol Lake where water samples were taken			
		Northern part	Southern part	Western part	Eastern part
General α -activity	0.2	0.037	0.073	0.056	0.044
General β -activity	1.0	0.042	0.033	0.048	0.061

Microbiological analysis showed that concentrations of lactose-positive coliform bacteria ranged from 1,170 to 1,230 CFU/L, remaining below the permissible limit (5,000 CFU/L). Coliphages were not detected, and parasitological examination revealed no helminth eggs (Table 4). These results confirm the sanitary safety of the lake water for recreational bathing and potential therapeutic use.

Table 4. Microbiological indicators of Alakol Lake water samples

Indicators	Max quantity in 1 l of water according to ST RK 3468-2019	Western part	Eastern part	Northern part	Southern part
Test results					
Lactose- positive bacillus	5000	1,220	1,170	1,200	1,230
Kolya phage	1000	-	-	-	-

Note. Laboratory test results of Alakol Lake water samples obtained in the accredited bacteriological laboratory of the Department of Sanitary and Epidemiological Control of the Zhetysu Region (2024–2025).

4.4. *Balneological potential and environmental implications*

The presence of biologically important elements (Mg, Mn, K, Ca, Na, Fe, Ba, Zn, Cu, Cr, and Ni) enhances the balneological value of both water and peloid deposits (Ivanišević, 1999; Smith & Puczkó, 2014; Szromek & Wybrańczyk, 2019). These elements contribute to metabolic and anti-inflammatory processes, while the therapeutic mud exhibits high adsorption capacity (Grafetstätter et al., 2017; Niedermeier et al., 2019).

The results indicate considerable potential for health and wellness tourism. Sustainable utilization, however, requires regulation of visitor pressure, effective wastewater treatment, solid-waste management, and continuous hydrochemical and microbiological monitoring (Butler & Szromek, 2019; Lee & King, 2010; Mueller & Kaufmann, 2001).

4.5. *Integrated Environmental Index*

An IEI was constructed by combining standardized hydrochemical, microbiological, and radiological indicators:

$$IEI = 1 / 3 (H+M+R) \quad (2)$$

where *H* – normalized hydrochemical score; *M* – microbiological compliance coefficient; *R* – radiological safety coefficient.

All microbiological parameters complied fully with national standards (compliance coefficient = 1.0), and alpha/beta activity remained below regulatory limits ($R \approx 1.0$). Hydrochemical compliance coefficients ranged from 0.78 to 0.94 across sectors.

The resulting IEI values varied between 0.86 and 0.95, indicating a high level of overall environmental safety and confirming the suitability of the water body for recreational and balneological use.

4.6. *Statistical variability of hydrochemical parameters*

Spatial heterogeneity was evaluated using coefficients of variation (CV). Total mineralization exhibited moderate variability (13.9–29.9%), whereas major cations (Mg^{2+} , Na^{+} , and Ca^{2+}) showed CV values of 11–43%, reflecting differences in groundwater contribution and river inflow.

Higher variability ($CV > 60\%$) was observed for Sb, Ba, Co, Zn, and Al, particularly in the western recreational sector, suggesting local anthropogenic influence. Mean values, standard deviations, and CVs confirmed hydrochemical differentiation among lake sectors.

Correlation analysis demonstrated a moderate positive relationship ($r = 0.52\text{--}0.67$) between total mineralization and Cl^{-} and Na^{+} concentrations, consistent with salt accumulation under restricted water exchange (Ren et al., 2022; Yapiyev et al., 2017). Overall, the results confirm significant spatial hydrochemical heterogeneity within the lake system.

4.7. *Recreational load and ecological pressure*

Recreational density was calculated as the ratio of daily tourist flow to the functional area of each recreational zone (Jónás-Berki et al., 2015; Papageorgiou & Beriatos, 2011, Figure 3, Table 5).

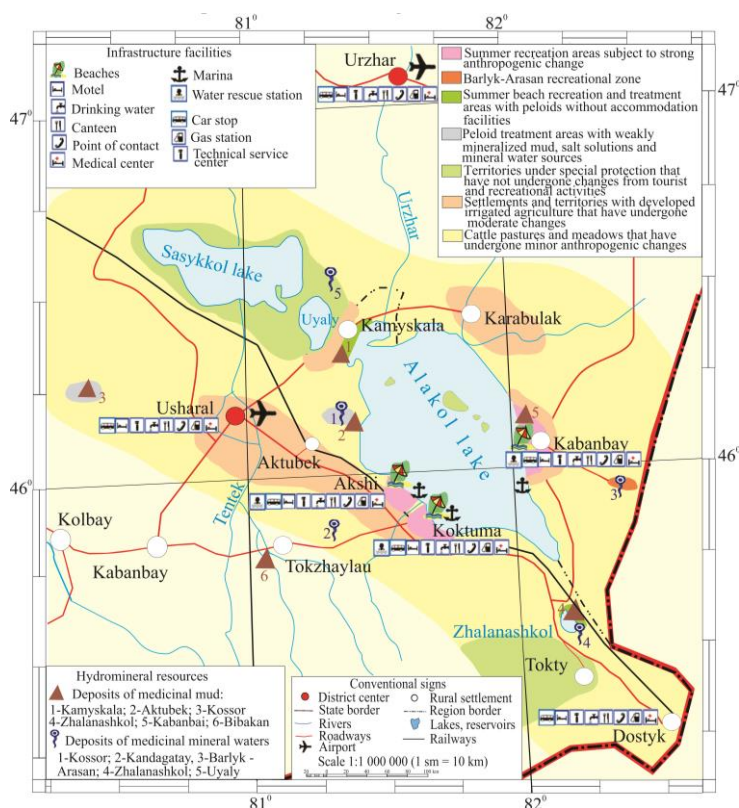


Figure 3. Map of recreational zoning of Alakol basin.

Note. Author's compilation based on the results of the present study.
 The figure was prepared using CorelDRAW.

Observed values ranged from 18.5 to 27.1 persons/ha. Compared to the recommended threshold for arid landscapes (≤ 5 persons/ha), this represents a 3.5–5.4-fold exceedance. Such intensity of use increases risks of soil compaction, vegetation degradation, shoreline erosion, and secondary contamination from wastewater and solid waste accumulation (Gössling et al., 2020; McCool & Bosak, 2016). In closed lake systems with limited self-purification capacity, prolonged exceedance of carrying capacity thresholds may induce cumulative hydrochemical alterations.

Table 5. Description of contents

Recreation areas	Number of large holiday homes	Daily tourist flow	Area of the recreation area (ha)	Recreational load per person/ha
Kabanbay	190	28,500	1,050	27.1
Koktuma	175	26,500	1,510	18.5
Akshi	210	33,600	1,730	19.4

5. Discussion

5.1. Hydrochemical heterogeneity and natural controlling processes

The 2024–2025 monitoring confirms that Alakol Lake is a naturally mineralized endorheic system with pronounced spatial hydrochemical heterogeneity. Total mineralization (1,450–2,070 mg/dm³) reflects the combined effects of evaporation, restricted water exchange, and salt accumulation under the arid continental climate of southeastern Kazakhstan. The positive relationship between mineralization and Na⁺ and Cl[−] concentrations supports the dominant role of evaporative concentration in shaping lake-water chemistry (Wurtsbaugh et al., 2017; Yapiyev et al., 2017).

Sectoral differences are controlled by river inflow, groundwater discharge, shoreline morphology, and evaporation. Lower mineralization in the southern sector reflects river inflow, whereas groundwater contributes to elevated concentrations of several elements in the eastern sector. The northern shallow-water zone is characterized by enhanced evaporative concentration. Increased variability of Sb, Ba, Co, and Zn in the western recreational sector suggests the onset of local anthropogenic influence associated with intensive tourism development (Medeu et al., 2023; Mukayev et al., 2023).

5.2. Sanitary safety and balneological value of hydro-mineral resources

Hydrochemical, microbiological, and radiological analyses confirm that the Alakol Basin currently satisfies national safety requirements for recreational and therapeutic use. Concentrations of major ions, trace elements, heavy metals, and microbiological indicators remained within permissible limits, while alpha and beta activity complied with radiation standards.

These findings support the considerable balneological value of the basin. The presence of Mg, Ca, Na, K, Fe, Ba, Zn, Cu, Cr, and Ni, together with the absence of hazardous contamination in bottom sediments, indicates favorable conditions for therapeutic applications. Nevertheless, preservation of these resources depends on preventing secondary pollution and maintaining geoeological stability (Barhoumi et al., 2019; Calin et al., 2019; Maraver et al., 2021).

5.3. Regional and international comparison of saline and mineral lakes

Compared with other saline lakes in Kazakhstan, Alakol represents an intermediate system between freshwater and hypersaline lakes. Internationally, it shares many characteristics with saline lakes in Eastern and Southern Europe, including endorheic hydrology, evaporative concentration, and therapeutic peloid formation. However, Alakol remains less affected by long-term resort development than lakes such as Tekirghiol, Amara, Pomorie, and Ursu.

Experience from European saline lakes demonstrates that uncontrolled recreational expansion may alter hydrochemical conditions and reduce the quality of therapeutic resources (Gössling et al., 2015; Wurtsbaugh et al., 2017). Consequently, the current favorable environmental conditions of the Alakol Basin should be regarded as both an opportunity and a management priority.

5.4. Recreational pressure and landscape carrying capacity

The principal geoeological threat identified in this study is excessive recreational pressure rather than chemical pollution. Recreational density exceeded the recommended carrying

capacity for arid landscapes by 3.5–5.4 times, increasing the risk of shoreline degradation, soil compaction, wastewater contamination, and accumulation of pollutants in sediments (Mukayev et al., 2020; Mukayev et al., 2023).

The coincidence of intensive tourism with increased trace-element variability in the western sector suggests that recreational development is already influencing local hydrochemical conditions. Although regulatory thresholds have not yet been exceeded, these changes may represent an early stage of anthropogenic transformation.

5.5. Implications for sustainable health and wellness tourism management

The results reveal a clear contrast between high environmental quality and excessive recreational pressure. Although the IEI (0.86–0.95) confirms favorable conditions for health and wellness tourism, visitor numbers already exceed the ecological carrying capacity of the coastal landscapes.

Future development should therefore prioritize environmentally responsible management rather than expand tourism infrastructure. Priority measures include visitor-capacity regulation, modern wastewater treatment, effective waste management, continuous hydrochemical and microbiological monitoring, and GIS-based management of recreational zones. Particular attention should be paid to the western sector, where tourism pressure is the greatest. Overall, sustainable use of the Alakol Basin depends on balancing tourism development with long-term geoecological stability.

5.6. Balneological significance and sustainability implications

The therapeutic value of the Alakol Basin is supported by favorable concentrations of biologically important elements and the adsorption capacity of therapeutic muds. However, despite high balneological potential (IEI > 0.85), recreational pressure already exceeds the ecological carrying capacity.

These findings emphasize the need for adaptive environmental management based on visitor limits, wastewater treatment, continuous monitoring of trace elements, and GIS-supported recreational zoning to preserve the long-term therapeutic and environmental values of the basin.

6. Conclusion

The geoecological assessment of the hydro-mineral resources of the Alakol Basin, based on field and laboratory investigations conducted in 2024–2025, demonstrated that this endorheic hydro-mineral system currently retains favorable environmental conditions despite the increasing recreational pressure. Natural mineralization, restricted water exchange, peloid formation, and tourism development interact within a fragile arid landscape, making the basin particularly sensitive to anthropogenic impacts.

Hydrochemical analysis revealed clear spatial differentiation controlled by hydrological conditions and local anthropogenic influences. Total mineralization ranged from 1,450 to 2,070 mg/dm³, while concentrations of major ions, trace elements, and potentially hazardous metals remained below the maximum permissible limits established by the sanitary regulations of the RK. Microbiological and radiological indicators also complied with national safety standards, confirming the suitability of the basin for recreational, wellness, and potential balneological use.

This study extends previous research on Kazakh saline lakes by providing the first integrated assessment of hydrochemical, microbiological, radiological, and recreational characteristics of the Alakol Basin within the ecological carrying-capacity framework. Unlike earlier studies that focused primarily on individual hydrochemical or tourism-related aspects, the present research links hydro-mineral resource quality with sanitary safety and recreational pressure, providing a more comprehensive basis for environmental management.

Although the basin currently maintains favorable hydrochemical and sanitary conditions, recreational density substantially exceeds the recommended ecological carrying capacity of the coastal landscapes. Continued tourism expansion without appropriate management may increase the risks of shoreline degradation, wastewater contamination, and gradual deterioration of hydro-mineral resources.

Therefore, the sustainable development of health and wellness tourism in the Alakol Basin requires an integrated environmental management strategy, including visitor-capacity regulation, modernization of wastewater infrastructure, improved solid-waste management, protection of vulnerable shoreline sectors, and continuous hydrochemical, microbiological, and radiological monitoring. Implementation of these measures will contribute to preserving the basin as an important hydro-mineral resource while ensuring its long-term geoecological stability in the arid regions of Zhetysu and Abai.

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