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GEOECOLOGICAL ANALYSIS AND EVALUATION OF MINERAL WATERS IN THE ALAKOL BASIN IN THE CONTEXT OF RECREATIONAL AND HEALTH TOURISM

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Geoecological analysis and evaluation of mineral waters in the Alakol basin in the context of recreational and health tourism

Abstract. The article presents a geo-ecological assessment of mineral waters in the Makachinsky district and examines factors influencing their quality and spatial distribution. The study aims to identify patterns of mineral resource formation and assess their environmental stability, with a focus on the region's recreational and tourism potential. The research is based on hydrogeochemical analysis, GIS technologies, and geo-ecological zoning methods. Field surveys and laboratory analyses of water samples were carried out, followed by cartographic data visualization. Key hydrogeochemical characteristics of mineral springs in the Alakol Depression were identified, including mineralisation level, acidity, and ionic and biochemical composition, enabling evaluation of their therapeutic value and suitability for tourism use. The study identifies natural territorial complexes with varying environmental resilience and recreational attractiveness, providing a basis for prioritising sites for sanatorium, resort, tourist, and hotel infrastructure. High-quality mineral waters and low anthropogenic pressure create favourable conditions for developing balneological, medical, wellness, and eco-tourism. The results can be applied to managing recreational load and monitoring mineral waters under tourist development, enabling the formation of sustainable tourist products, rational resource use, and improved hospitality services in the region.

Key words: tourism development, recreational potential, Alakol Basin, mineral waters, rational use.

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Рекреациялық және сауықтыру туризмі контекстінде Алакөл ойпатының минералды суларын геоэкологиялық талдау және бағалау

Аңдатпа. Мақалада Макачинск ауданының минералды суларының жағдайын геоэкологиялық бағалау қарастырылады және олардың сапасы мен таралуына әсер ететін факторлар талданады. Зерттеудің негізгі мақсаты-аймақтың рекреациялық және туристік мүмкіндіктеріне баса назар аудара отырып, минералды ресурстардың қалыптасу заңдылықтарын және олардың экологиялық тұрақтылығын анықтау. Зерттеудің әдіснамалық негізі гидрогеохимиялық талдау, геоақпараттық технологиялар және геоэкологиялық аймақтарға бөлу әдістері болды. Деректердің картографиялық визуализациясымен су сынамаларын далалық бақылаулар мен зертханалық зерттеулер жүргізілді. Алакөл ойпатының минералды көздерінің минералдану деңгейін, қышқылдығын, иондық және биохимиялық құрамын қоса алғанда, олардың емдік-сауықтыру құндылығын және туристік пайдалануға жарамдылығын бағалауға мүмкіндік беретін негізгі гидрогеохимиялық параметрлері анықталды. Зерттеуде экологиялық тұрақтылығы мен рекреациялық тартымдылығы әртүрлі табиғи-аумақтық кешендер айқындалды, бұл санаторий-курорттық, туристік және қонақүй инфрақұрылымын орналастыруды басымдықпен жоспарлауға негіз болады. Минералды сулардың жоғары сапасы мен антропогендік жүктеменің төмен деңгейі бальнеологиялық, емдік-сауықтыру және экотуризмді дамыту үшін қолайлы жағдай жасайды. Алынған нәтижелер аумақты туристік игеру жағдайында рекреациялық жүктемені басқару және минералды сулардың жай-күйін мониторингтеу жүйесін ұйымдастыруда пайдаланылуы мүмкін, бұл орнықты туристік өнімдерді қалыптастыруға, табиғи ресурстарды ұтымды пайдалануға және өңірдегі қонақжайлылық қызметтерінің сапасын арттыруға ықпал етеді.

Түйін сөздер: туризмді дамыту, рекреациялық әлеует, Алакөл ойпаты, минералды сулар, ұтымды пайдалану.

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Геоэкологический анализ и оценка минеральных вод Алакольской впадины в контексте рекреационного и оздоровительного туризма

Аннотация. В статье рассматривается геоэкологическая оценка состояния минеральных вод Макачинского района и анализируются факторы, влияющие на их качество и распределение. Основная цель исследования – выявление закономерностей формирования минеральных ресурсов и их экологической устойчивости, с акцентом на рекреационные и туристские возможности региона. Методологической основой исследования послужили гидрогеохимический анализ, геоинформационные технологии и методы геоэкологического зонирования. Проведены полевые наблюдения и лабораторные исследования проб воды с последующей картографической визуализацией данных. Определены основные гидрогеохимические параметры минеральных источников Алакольской впадины, включая уровень минерализации, кислотность, ионный и биохимический состав, позволяющие оценить их лечебно-оздоровительную ценность и пригодность для туристского использования. В исследовании выделены природно-территориальные комплексы с различной экологической устойчивостью и рекреационной привлекательностью, что служит основой для приоритизации размещения санаторно-курортной, туристской и гостиничной инфраструктуры. Высокое качество минеральных вод и низкая антропогенная нагрузка создают благоприятные условия для развития бальнеологического, лечебно-оздоровительного и экотуризма. Полученные результаты могут быть использованы для управления рекреационной нагрузкой и организации мониторинга состояния минеральных вод в условиях туристского освоения территории, способствуя формированию устойчивых туристских продуктов, рациональному использованию природных ресурсов и повышению качества услуг гостеприимства в регионе.

Ключевые слова: развитие туризма, рекреационный потенциал, Алакольская впадина, минеральные воды, рациональное использование.

Introduction. Mineral waters are important natural resources [1] with significant recreational and health potential. In scientific literature, these springs represent a fundamental component of geo-ecological systems, affecting both the environmental state of the area and the region's socio-economic development, especially in the field of tourism and health improvement.

The Makachinsk district of the Abai region is known for its unique balneological resources, including chloride-sodium type mineral waters with a complex of natural biochemical characteristics. Research into the composition and biochemical characteristics of mineral waters [2-4] has been ongoing since the end of the 20th century, but in recent years there has been a significant increase in interest in assessing the sustainability of these resources in the context of growing anthropogenic impact [5, 6].

Environmental monitoring [7] has revealed that the active development of tourism [8], especially during the summer period, leads to increased pressure on the region's natural complexes, manifested in coastal pollution [9], uncontrolled extraction of mineral water and degradation of natural sources [10]. In this regard, a number of researchers emphasise the need to develop and implement sustainable natural resource management systems [11], including zoning of territories [12], recreational control [13] and environmental auditing [14].

In international practice, the sustainable use of balneological resources is achieved through the integration of geo-ecological approaches [15, 16] such as landscape structure analysis, hydrogeochemical assessment of water bodies and modelling of the impact of recreational load on the environment [17, 18]. In Kazakhstan, such comprehensive methods are still used to a limited extent, which opens up prospects for regional studies with a systematic approach.

Despite the existence of individual studies on the chemical composition of mineral waters in the Makachinsky region, a systematic approach combining issues of effective use, protection and assessment of the geo-ecological state remains underdeveloped. This confirms the relevance of a comprehensive analysis, including geo-ecological assessment, recreational planning and monitoring of the sustainability of natural resources.

The object of the study is the mineral waters of the Makanchinsk district. The subject of the study is their geo-ecological condition, biochemical properties and possibilities for rational use**. The purpose** of this research is to evaluate the geo-ecological status of the mineral waters with regard to principles of sustainable environmental management.

To achieve this goal, the following **objectives of the study** were set:

– to analyse existing studies on the balneological resources of the region;

– to determine the chemical and biochemical characteristics of the objects under study;

– to identify geo-ecological risks associated with anthropogenic pressure.

The research hypothesis is that the balanced use of mineral waters is possible provided that a system

of geo-ecological monitoring and spatial planning is implemented.

The study of mineral waters in Kazakhstan has a long scientific tradition. The suitability of the fissured mineral waters of the Alakol Depression for the development of medical and sanatorium activities has been studied for several decades.

Between 1930 and 1950, balneologist M.S. Lavrov, climatologist N.N. Korostelev and chemical engineer E.E. Karters conducted comprehensive studies of the chemical composition and thermal characteristics of the springs, substantiating their therapeutic value and classifying them according to balneological criteria.

Between 1960 and 1970, research was further conducted by specialists from the sanatorium and resort surgery department of the Institute of Medical and Experimental Surgery of the Kazakh SSR Academy of Sciences, including B.A. Atshabarov, Sh. Sabdenov, S.I. Zamyatin, M.S. Kan, A.I. Zubashev, and L.G. Goldfeil [19].

They systematised all mineral waters according to their physical and chemical properties, determined their thermal, hydrogeochemical and biologically active characteristics, and established the optimal directions for their use in therapeutic, prophylactic and sanatorium-resort practice.

In recent studies [20], fissure waters have been classified according to hydrochemical parameters and the ecological condition of deposits has been assessed in the context of growing tourist pressure. The rational use of mineral resources is directly linked to the development of recreational infrastructure and the improvement of environmental regulation [21-23].

Foreign authors consider the problem of sustainable management of balneological resources from the perspective of geo-ecological analysis and spatial modelling [24, 25] and emphasise the need to assess the sensitivity of landscapes when designing tourist facilities.

A comparative analysis of the literature shows that Kazakhstan still lacks a unified system for geo-ecological monitoring of balneological facilities. This determines the scientific novelty of this study, which aims to integrate hydrochemical, biochemical, and ecological approaches to the study of mineral waters.

Materials and methods. The study is based on field, laboratory and analytical methods. Mineral water samples collected in the vicinity of Mount Arasanta and the coast of Lake Alakol were used as source material. Quantitative parameters included chemical composition (ionic analysis, determination of Fe, Mn, Pb, Zn concentrations), biochemical indicators (content of organic compounds, microbiological activity), as well as organoleptic characteristics (colour, smell, consistency).

Laboratory studies were conducted using spectrophotometric and potentiometric analysis, verified according to SS 31940–2012 and ISO 10523:2012 methods. Variational analysis and statistical data reliability assessment methods were used to process the results.

During the laboratory studies, the biochemical and organoleptic composition of mineral waters was analysed, including indicators of colour, odour, consistency and structure. The results of the analysis showed that the waters under study contain detergents and heavy metals, but the concentrations of these pollutants do not exceed the established sanitary standards.

As part of this study, aimed at a comprehensive analysis of the state, rational use and protection of mineral waters in the Makachinsky District, a set of scientific methods was applied, ensuring a systematic approach to the assessment of natural resources, taking into account geo-ecological conditions. The methodological basis of the study included a combination of field (expedition) and office-based methods, as well as the use of both qualitative and quantitative approaches to information analysis.

One of the basic methods used in the study was geo-ecological zoning of the territory. This made it possible to identify separate natural-territorial complexes within the Makachinsky District, with varying degrees of suitability for recreational development, as well as varying vulnerability to anthropogenic impact. The zoning was carried out on the basis of a comprehensive analysis of geomorphological, climatic, hydrogeological and biotic characteristics. In addition, natural resources were classified according to their degree of mineralisation, therapeutic potential, accessibility and ecological status.

A comprehensive study of the components of the natural environment was carried out in order to identify the patterns of formation and functioning of geo-ecosystems within which mineral water sources are concentrated. Particular attention was paid to the hydrogeological conditions of mineral water formation and the typology of waters according to

their chemical composition. The climatic features, soil types, vegetation structure and dynamics of the water-mineral balance of the region were also analysed.

In order to visualise the results and interpret the data spatially, thematic mapping methods were used with the application of geoinformation technologies. A map showing the distribution of mineral springs was developed. Spatial analysis made it possible to identify areas with the greatest recreational and health potential.

During the expedition, samples of mineral waters were collected and subsequently subjected to laboratory analysis. Biochemical studies included the determination of acidity (pH), degree of mineralisation, content of major ions, trace elements and gases. Microbiological analysis was aimed at identifying sanitary and hygienic indicators, including the presence of pathogenic microorganisms and the total microbial count.

Results. The mineral springs of the Alakol Depression are spatially confined to elevations of about 605 m above sea level, within the coordinates 46°06’29‘N and 82°17’57’ E. The geomorphological structure of the territory is characterised by a gentle slope in the south-easterly direction, towards the depression where Lake Alakol (347 m above sea level) is located. This morphometric organisation creates natural drainage conditions, ensuring the directed migration of groundwater to the central part of the basin.

According to hydrogeological observations, mineral waters are formed within the zone of distribution of grey-red biotite granites with developed fracturing. This contributes to the infiltration of atmospheric precipitation and the subsequent accumulation of groundwater in the upper horizons of the geological section.

The average flow rate of the springs varies between 1.1 and 1.6 litres per minute, and the water temperature is 17–21 °C, which indicates a shallow aquifer and the absence of a pronounced geothermal gradient.

The spatial structure of the springs and their geo-ecological parameters were analysed using geoinformation technologies, which made it possible to construct a map of the distribution of the springs.

Laboratory tests showed that the mineral waters are weakly mineralised (329–374 mg/dm³). All samples are characterised by high transparency, absence of odour and a temperature regime typical for cold groundwater, which confirms their natural origin and absence of anthropogenic impurities (Table 1).

Table 1 – Main parameters of mineral springs based on field observations

Indicators/ Sources	S1	D2	S3	S4
Temperature, °C	21°C	19°C	20°C	17°C
Odour	odourless	odourless	odourless	odourless
Transparency	transparent	transparent	transparent	transparent
Taste	bitter	bitter	bitter	sour
Geographical coordinates	46°06’29 n.l. 82°17’57» e.l.	46°06’29 n.l. 82°17’57» e.l.	46°06’29 n.l. 82°17’57» e.l.	46°06’29 с.ш. 82°17’32» e.l.
pH	8.83 (slightly alkaline environment)	8.52 (slightly alkaline environment)	8.52 (slightly alkaline environment)	7.02 (neutral environment)

The reaction of the environment varies from neutral (pH 7.0) to slightly alkaline (pH 8.5–8.8). This range of pH values indicates the presence of hydrocarbonate ions and points to the interaction of groundwater with silicate rocks characteristic of granitoid complexes.

Hydrochemical investigations revealed that the water’s anionic composition corresponds to the sulphate-hydrocarbonate-chloride type, whereas the cationic composition is characterised by the presence of potassium, sodium, calcium, and magnesium ions.

Table 2 – Hydrochemical characteristics of fissured mineral waters based on spectral analysis results

Indicators	Chemical composition of water sources				Indicators	Chemical composition of water sources			
	1	2	3	4		1	2	3	4
Odour, score	0	0			K, mg/dm^3	14.09	9.97	13.7	13.41
Transparency	30	30			Li, mg/dm^3	0.45	0.15	0.41	0.40
pH	8.83	8.5	8,7	7.62	Srmg/dm^3	0.39	0.05	0.35	0.34
Total mineralisation, mg/dm^3	939	269	888	741	Chlorides, mg/dm^3	33,1	33,1	33,1	30,2
Hardness, mmol/dm^3	1,41	1,25	1,34	1,18	Sulphates, mg/dm^3	167,2	176,4	144,6	147,3
Dry residues, mg/dm^3	83,0	86,0	80,1	85,0	HCO_3, g/dm^3	61,5	46,3	53,8	42,6
Alkalinity moles/dm^3	1,1	0,73	1,11	0,77	Phosphates,mg/l	2,45	2,88	2,71	2,34
Simg/dm^3	19.88	7.42	17.5	14.04	F mg/dm^3	0,001	0,002	0,002	0,001
Ca, mg/dm^3	160.5	34.8	144.0	130.28	Fluorides, mg/dm^3	0,003	0,005	0,005	0,002
Mg, mg/dm^3	2.72	9.26	1.09	0.79	NH_4^+, mg/dm^3	0,003	0,001	0,001	0,001
Fe, mg/dm^3	0,22	0,18	0,20	0,17	H_4SiO_4 mg/dm^3	36,0	38,3	37,2	0,001
B	5.95	5.14	5.82	5.47	Nitrates, mg/dm^3	-	-	-	-
Sodium + potassium, mg/dm^3	82,6	81,7	79,3	80,7					

The water exhibits a hardness ranging from 1.18 to 1.41 mmol/dm³, categorising it as soft and suitable for sanitary and balneological applications. This low hardness is attributed to the comparatively small concentrations of calcium and magnesium ions, resulting from the leaching of silicate minerals.

Total mineralisation varies from 329 mg/dm³ (I4) to 374 mg/dm³ (I2), reflecting local differences in filtration conditions, degree of mineralisation and length of the underground water path.

Figure 1 shows the ratio of the main ions that make up the chemical composition of the mineral waters of S1 in the Alakol Depression. Analysis of the diagram shows that the waters are dominated by anions of the sulphate (SO_4^{2-}) and bicarbonate (HCO_3^-) groups, while the cations are dominated by calcium (Ca^{2+}) and sodium with potassium (Na^++K^+).

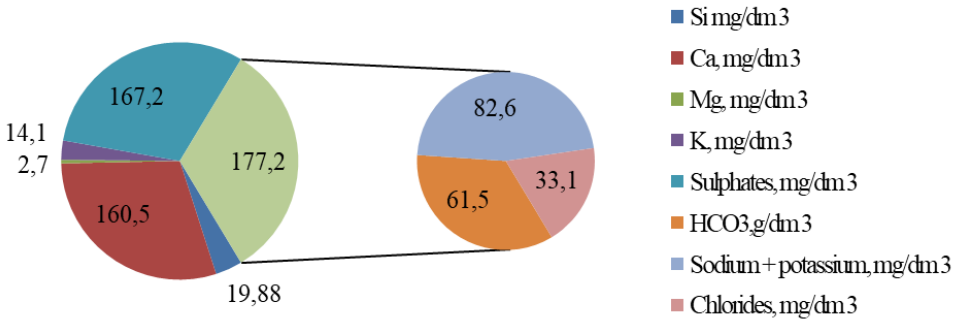

Figure 1 – Ion composition of mineral waters S1

Sulphates (177.2 mg/dm³) and calcium (160.5 mg/dm³) account for the largest share of the composition, indicating gypsum-bearing and carbonate-sulphate types of aquifers

Chemical analysis of the mineral water from source S2 reveals the highest levels of sulphates (SO_4^{2-} = 176.4 mg/dm³) and magnesium (Mg^{2+} = =161.1 mg/dm³), indicating a sulphate-magnesium composition and reflecting the interaction of groundwater with gypsum– and dolomite-bearing rocks within fractured granitoid formations.

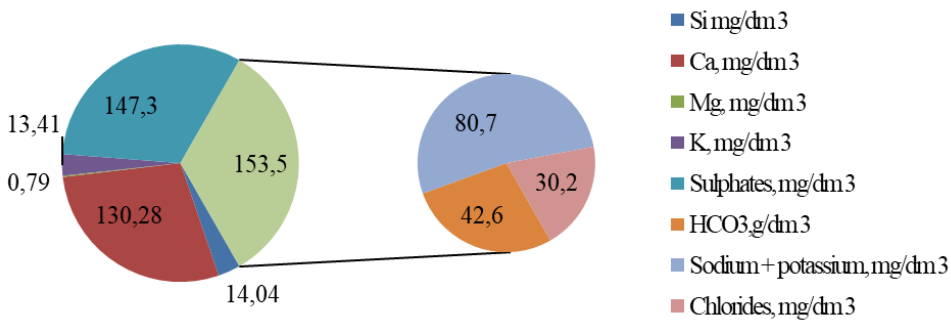

Figure 2 – Ion composition of mineral waters S2

The predominant components of mineral waters from source S3 are sulphates (SO_4^{2-}=144.6 mg/dm³) and magnesium (Mg^{2+}=166.2 mg/dm³), which indicates that these are sulphate-magnesium type mineral waters (Figure 3).

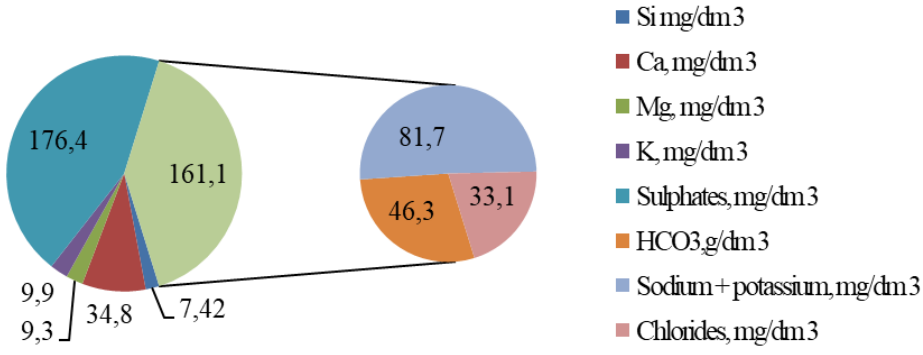

Figure 3 – Ion composition of mineral waters S3

The cationic profile of water from source I4 is primarily composed of magnesium (Mg^{2+} = 166.2 mg/dm³) and calcium (Ca^{2+} = 144.0 mg/dm³), indicating elevated hardness, likely resulting from flow through magnesia-calcium lithologies (Figure 4). The notable silicon content (Si = 144.6 mg/dm³) suggests saturation with silicon dioxide derived from silicate rocks, a characteristic feature of subterranean or thermal waters.

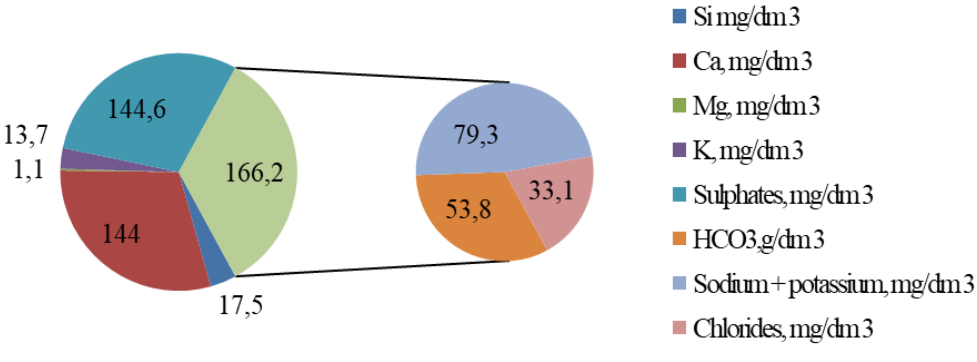

Figure 4 – Ion composition of mineral waters S4

The water from all four sources is characterised by the presence of a wide range of dissolved substances, reflecting the processes taking place within the aquifers.

Figures (Figures 1–4) clearly show the dominance of sulphate and hydrocarbonate ions in the composition of anions, and among cations, the predominance of calcium, magnesium, sodium and potassium ions.

The mineral springs of the Alakol Depression have significant recreational potential, especially for balneological use. The waters are characterised by moderate mineralisation (329–374 mg/dm³), which makes them suitable for therapeutic purposes, such as mud therapy, mineral baths, thermal resorts, and spa treatments. The high content of hydrocarbonates and sulphates in the water indicates its beneficial properties for the treatment of musculoskeletal disorders, skin diseases and other chronic diseases.

In order to visualise the spatial distribution and integrate the data obtained into practical nature management, a schematicmap of "Hydromineral recreational resources of the recreation and health tourism zone in the eastern part of Lake Alakol" was developed based on the results of field expedition studies conducted in the region (Figure 5).

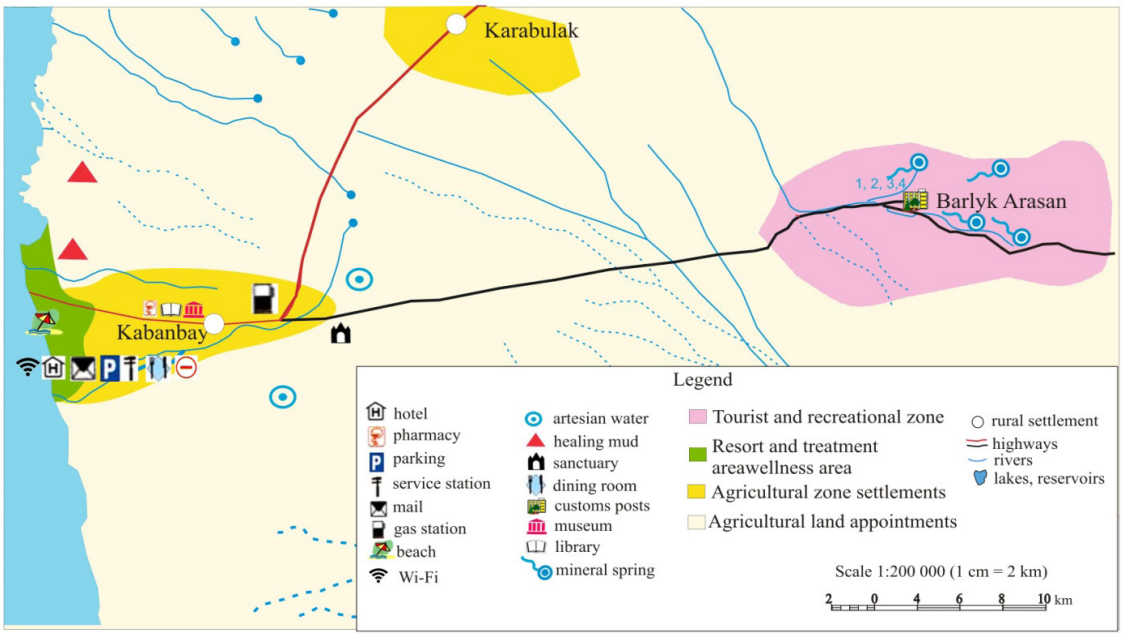

Figure 5 – Schematic map of hydromineral recreational resources in the recreation and health tourism zone in the eastern part of Lake Alakol

The schematic map is a functional tool for territorial planning that facilitates decision-making on the development of sustainable tourism, balneology and the protection of natural resources in the eastern part of Lake Alakol.

Discussion. The analysis of the mineral waters in the Alakol Depression reveals that the chemical composition is largely determined by the interaction of groundwater with the underlying granitoid rocks. High concentrations of sodium and potassium (82.6 mg/dm³) in source S1 are associated with ion exchange processes between water and feldspar minerals, indicating prolonged interaction with crystalline basement rocks. The presence of hydrocarbonate ions (61.5 mg/dm³) reflects the leaching of silicate minerals and the influence of CO_2 from both soil air and the atmosphere, while chloride concentrations (33.1 mg/dm³) remain low, suggesting minimal anthropogenic impact and limited connection with surface waters.

Silicic acid (Si=14.1 mg/dm³) and potassium (K=19.9 mg/dm³) confirm the natural mineralisation process during groundwater circulation through granite and biotite-rich rocks. These elements, along with the detected trace microelements, potentially contribute to the therapeutic and prophylactic properties of the springs. Based on total ionic composition, waters from source S1 are classified as sulphate-hydrocarbonate-calcium-sodium type with moderate mineralisation, supporting their suitability for balneological and recreational purposes.

Source S2 exhibits moderate mineralisation with a balanced cation–anion ratio, classified as sulphate-hydrocarbonate-magnesium-sodium type. The elevated calcium (Ca^{2+}=144 mg/dm³) and magnesium (Mg^{2+}=166.2 mg/dm³) levels indicate interaction with gypsum-bearing and carbonate rocks, along with secondary enrichment through prolonged filtration in fractured granitoid zones. Hydrocarbonates (HCO_3^-=46.3 mg/dm³) and stable chloride values (Cl^-=33.1 mg/dm³) further confirm the natural origin of these waters, unaffected by anthropogenic activity.

The chemical composition of source S3 is characterised by sulphate-hydrocarbonate-magnesium-calcium dominance and a slightly alkaline pH (8.5–8.7), indicating weakly mineralised, naturally filtered groundwater. Ionic ratios show stable trends for calcium, magnesium, sodium, and potassium, reflecting ion exchange with silicates and feldspar, as well as leaching from biotite granites. Low concentrations of fluorine and nitrogen compounds corroborate the ecological purity of this source.

Source S4 demonstrates high hydrocarbonate content (HCO_3^-=79.3 g/dm³), alongside moderate concentrations of sulphates and chlorides, consistent with natural mineralised waters influenced by magnesia-calcium lithologies. Sodium and potassium contents are typical for natural waters, with potassium present only in trace amounts. Overall, the water chemistry across all sources reflects sulphate-hydrocarbonate dominance, moderate mineralisation, and minimal anthropogenic influence, confirming that the observed hydrochemical characteristics are the result of natural geochemical processes, including filtration, mineral dissolution, and ion exchange.

The chemical composition of mineral waters studied in the Alakol Depression confirms their high therapeutic value. Low pollution levels and favourable geo-ecological conditions create opportunities for the development of medical tourism, including the creation of sanatoriums and resort complexes offering various types of balneological procedures. These sources can become an important part of the regional tourism infrastructure, contributing to the development of environmentally friendly tourism and attracting tourists for health purposes.

The mineral resource distribution scheme that has been created is an important tool for planning the recreational use of the territory, in particular for the development of tourist and health facilities. The recreational areas developed, taking into account geo-ecological characteristics, can become the basis for the sustainable development of medical and spa tourism, taking into account the minimisation of anthropogenic impact and the protection of natural resources. It is also necessary to introduce a monitoring system that will allow control of water quality and ensure its long-term and rational use for recreational purposes.

Conclusion. Geoecological analysis of mineral waters in the Alakol Depression and spatial interpretation of their distribution have revealed the main patterns of formation, quality and recreational potential of the region's hydro-mineral resources. The results obtained are of significant practical importance for the tourism and hospitality sector, as they create a scientifically sound basis for the development of balneological, medical and health, and ecological tourism, as well as for the creation of competitive tourism products focused on the use of natural healing factors.

During a comprehensive study of the mineral waters of the Makachinsky District, key geo-ecological factors determining their distribution and quality were identified. The confirmed high natural purity of mineral waters and the minimal level of anthropogenic impact allow us to recommend their use in the practice of sanatorium-resort treatment, health recreation and the functioning of tourist and hotel infrastructure facilities without a significant risk of degradation of natural resources.

The developed scheme for the use of mineral springs for recreational and therapeutic purposes, as well as the created schematic map of their spatial distribution, can be used as tools for territorial planning in the field of tourism and hospitality. They provide the opportunity to zone the territory according to recreational use regimes, justify the location of sanatorium, resort, tourist and hotel facilities, and assess the permissible recreational load, taking into account environmental constraints, which contributes to the sustainable development of the tourist destination.

In the future, it would be advisable to expand research in the direction of managing recreational load and organizing systematic monitoring of the condition of mineral waters in the context of tourist development of the territory. The implementation of these measures will make it possible to identify changes caused by natural and anthropogenic factors in a timely manner, ensure the protection of mineral sources and maintain their healing properties. The identified recreational potential of the territory allows us to recommend the development of comprehensive programs for the sustainable development of resort areas, aimed at the rational use of hydro-mineral resources, improving the quality of tourist services and the competitiveness of the region's hospitality sector.

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