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Lithium Concentrations in Saline Brines of the Shu–Sarysu Depression

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Abstract: This article presents the results of a study on lithium mineralization in salt flats and underground aquifers of the Shu–Sarysu depression. Analysis of brine samples collected from 2022 to 2023, utilizing spectroscopy and X-ray diffraction, reveals elevated concentrations that hold commercial promise. These findings may have significant implications for exploration efforts and estimation regarding the lithium resource potential, which is currently in high demand. This article examines data regarding lithium brine deposits worldwide, focusing on their geology. The research methodology involves delineating regions of salt flat distribution through remote sensing data interpretation, fieldwork, and laboratory analysis, particularly for surface brines. Underground lithium-bearing brines are detected within oil and gas structures. The article presents findings from analytical studies conducted on saline and co-produced formation brines collected during the 2022 field season, with a specific focus on the epiplatform regions of Kazakhstan, encompassing the Shu–Sarysu depression.

Keywords: lithium mineralization; saline brine deposits; salt flats; Shu–Sarysu depression

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1. Introduction

According to experts in the field, there is a projected threefold increase in the demand for lithium by the year 2028, with an estimated annual consumption ranging from 550,000 to 600,000 tons [1]. Furthermore, there has been a substantial surge in the price of lithium carbonate between 2021 and 2022, soaring from USD 55,000 to USD 327,500 [2]. Various experts, as referenced in sources [3,4], estimate the global lithium resources at a staggering 13 million tons, while the current global consumption stands at 65,000 tons annually. It is worth noting that 22% of the confirmed lithium resources are concentrated in pegmatite deposits, while the remaining 78% can be found in continental brine sources [1].

At present, the primary lithium producers are located in Latin American countries, Australia, and China [1–4]. In Australia, the primary source of lithium comes from pegmatites, whereas in Latin American countries and China, lithium production relies on the exploitation of hydro-mineral resources (Salar de Atacama, Chile; Salar de Uyuni, Bolivia; Salar del Hombre Muerto, Argentina; a series of salt flats in the Qinghai–Tibet Plateau, China) [2–6].

An examination of the factors influencing the formation of salt flats in South America, Tibet, and Mongolia yields the following conclusion: the Li_2O content within the waters of the final runoff reservoirs is governed by several factors, including the lithium content in the groundwater and subterranean waters, the level of brine mineralization, the tectonic and volcanic activity within these regions, as well as the prevailing climatic conditions. These combined factors can result in the repeated precipitation of highly soluble salts, ultimately leading to the enrichment of brine with lithium. Furthermore, the depressions

of tectonic origin that encompass the salt flats, along with their associated drainage basins, serve as natural geomorphological and structural traps where the accumulation of easily mobile and soluble components, such as lithium, takes place [4].

The findings from saline brine deposits highlight the importance of conducting exploration for critical elements, including lithium, in Kazakhstan. First of all, the Caspian basin, in which salt deposits have long been exploited for the extraction of halite, sylvite, gypsum, boron, and magnesite, is favorable for the exploration of lithium brine deposits in Kazakhstan. Saline brine deposits of this nature are extensively found in the region, including the desiccating Aral Sea, the Shu–Sarysu salt flats, and potentially the salt lakes in the Ertis River region. Nevertheless, the extraction of valuable components from Kazakhstan's salt flats has remained at a rudimentary stage, despite the fact that mineralized waters in many cases contain a diverse array of components [7].

Lithium is extracted from three types of deposits: "hard-rock" pegmatites, continental brines in "salars", and hydrothermally altered clays. Brine deposits account for around 75% of the world's lithium, due to lower costs of extraction [2–5]. Li-rich brines are found predominantly in basins of internal drainage or salars which are mainly located in the Andes in the Lithium Triangle countries. They are endorheic basins, meaning that the only exit for the inflowing water is via evaporation. This means that water, rich in lithium, flows to the salars and is then evaporated, resulting in the deposition of minerals. Over long time periods (~Ma), high-density brines collect in a nucleus that contains economic concentrations of lithium which is then pumped out. Whilst extraction from rocks requires a hydrometallurgical process (crushing and heating), extraction from brines, i.e., saline aquifers, involves the pumping from the shallow subsurface and a set of solar evaporation ponds where the liquid solution is moved from one to another until a desired concentration, or "purity", is reached. In this process, other components are removed by either precipitation or chemical reactions through the introduction of reagents. This is necessary since lithium coexists in brines with other elements, such as magnesium, that are noneconomic. To be noted, the evaporation/precipitation process is a slow one, taking one to two years from the water pumping to the processing of the concentrated brine in the processing plant, where further processing is employed to produce lithium carbonate [8].

The studied salt flats are situated within the tectonic Shu–Sarysu depression, notable for the extensive drainage rivers Shu and Sarysu. This depression is delineated by the Shu-Ile mountains to the east, the Betpak-Dala plateau to the north, and the Karatau mountains to the southwest [9].

2. Geological Characteristics of the Study Area

The research area (Figure 1) encompasses over 1500 square kilometers and is situated within the administrative boundaries of Kazakhstan's Turkistan and Kyzylorda regions. Geomorphologically, the study zone is characterized by a relatively undulating topography, featuring a combination of low gentle hills and extensive flat lowlands. These lowlands are dominated by vast takyrs and salt flats, some of which extend over a distance of 30 to 40 km.

The territory of the Shu–Sarysu Depression, due to the low annual precipitation and high aridity of the climate, belongs to the semi-desert and desert regions with a very poorly developed hydrographic network, featuring two relatively large rivers, the Shu and the Sarysu. The number of sunny days per year in the region exceeds 3000 h and the amount of precipitation is less than 100 mm per year [10,11].

The Shu and Sarysu valley comprises a gently undulating plain, spanning up to 40 km in width. Across its surface, there are isolated areas of aeolian sands, numerous salt flats, lakes, and dry beds of seasonal watercourses. During periods of water flooding, the river's water exhibits a slightly increased salinity relative to fresh water, while in the summer, as it lingers in the reaches, its total dissolved solids (TDSs) exceed 10 g/L. The alluvial plain consists of mixed-grained sands with gravel and pebbles, sandy loams, and, in the

downstream, loams, fine-grained sands, clays, and lacustrine sediments, often covered with salt deposits. The thickness of these deposits ranges from a few meters to over 40 m. The watered portion extends between 2 and 15 m in depth. The water table fluctuates between 1 and 5–9 m, with an amplitude of 0.6–1 m. Flow rates at water points vary from 2 to 86 m^3/day, occasionally reaching 172 m^3/day (2 L/s). Within the river's floodplain region, the waters tend to be predominantly salty, with only slight brackishness in some areas. On terraces and near the river's mouth, TDS can reach 10–50 g/L or even higher [10].

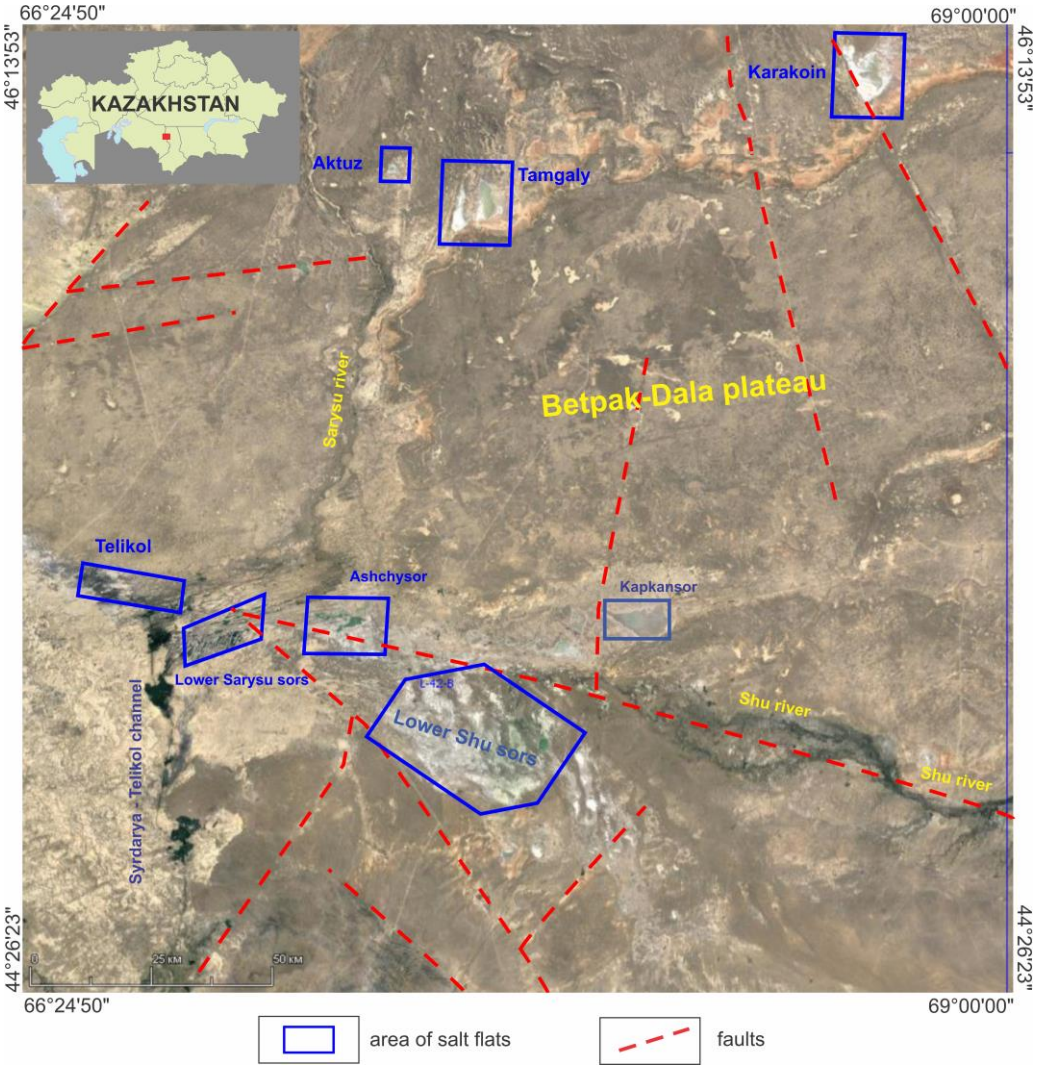

Figure 1. Salt flats investigated in the Shu–Sarysu Depression (Base map from Google Earth).

The chemical composition of groundwater is predominated by sodium sulfates and chlorides. Groundwater is replenished by filtration of the Shu and Sarysu river waters and atmospheric precipitation. Water is lost through transpiration by vegetation and evaporation, which is many times greater than the annual amount of precipitation.

In the study area, the following formations are identified: (1) Middle Quaternary sediments are present on the valley sides, comprising fine-grained sands with interlayers of loams, measuring 0.7–0.9 m in thickness. The total sediment thickness amounts to 8.0 m. (2) Middle-Upper Quaternary formations occupy the channels of temporary streams and the broad valleys of the ancient hydrographic network. These formations consist of proluvial loams, sandy loams, and sands, with a total deposit thickness of 5.5 m. (3) Upper Quaternary sediments constitute the takyr terrace of the Syrdarya River, overlaying the eroded surface of the Upper Cretaceous and Paleocene. These sediments are

composed of sandy loams, loams, and fine-grained sands, with a thickness ranging from 3.8 to 7.0 m. (4) Present-day Quaternary sediments are extensively distributed and predominantly consist of takyrs and salt flats, ranging in size from several hundred meters to several kilometers. Proluvial takyrs consist of loams and clays, occupying depressional landforms. Within the depressions between the hills, which are composed of reddish Upper Cretaceous sediments, loam and clay are prevalent. The lower strata of the takyrs consist of clays, with the upper part containing a mixture of sandy material. The overall thickness, mainly composed of sands and sandy loams, amounts to 15.0 m. (5) Aeolian formations are found on Middle to Upper Quaternary and contemporary sediments, creating accumulations of small ridges and fine hillocks comprised of aeolian sands that exhibit hues of yellowish-gray and grayish-yellow. (6) Lake sediments consist of clays, sands, and salts of complex mineral composition, with depths varying between 1.5 m and 14.0 m.

In terms of tectonics, the Shu–Sarysu depression is characterized as an intermountain hollow that emerged during the Carboniferous and Permian periods. The geological makeup of its pre-Hercynian base remains inadequately understood. The lower segment of the epi-Caledonian cover predominantly consists of Carboniferous deposits, comprising both terrigenous and carbonate formations, which are subsequently overlain by Permian formations characterized by a mix of carbonate, terrigenous, and saline materials. The Hercynian shifting in this region was notably feeble, with the overall tectonic activity resembling that of a platform. The geological structure of the area involves formations from the pre-Paleozoic and Paleozoic eras, capped by a Mesozoic–Cenozoic platform layer [10].

Within the Middle-Upper Paleozoic deposits, we observe Devonian volcanic-sedimentary rocks and their associated tuffs, which have undergone low- to very-low-grade metamorphism. As we move up the section, these materials transition into reddish conglomerates and sandstones, eventually giving way to dolomitized limestones, aleurolites, and argillites of the Lower Carboniferous. These formations commonly feature layers of rock salt, gypsum, and anhydrite. The Upper Paleozoic rocks of the Shu–Sarysu depression comprise red and gray sandstones alongside fine-grained conglomerates. Additionally, we find terrigenous red marls, argillites, and sandstones, with occasional occurrences of Permian limestones. Salt deposits are noticeable in the middle part of the section. The rock layers show minor displacement, with numerous disruptions recorded across all surveyed local structures, affecting both dome-shaped and sloped formations. The zone containing subterranean brine, as observed in vertical cross-sections, is associated with Paleozoic sedimentary and sedimentary–volcanic complexes. The water in this zone is artesian and rich in sodium chloride, exhibiting mineralization levels ranging from 60.6 to 253.8 g/kg at sampling depths reaching up to 2236 m [10].

The selection of the Shu–Sarysu depression as a promising area for exogenous lithium mineralization is primarily due to the fact that the rivers Shu and Sarysu are quite extensive and flow through large of volcanic-plutonic belts leaching easily soluble alkali metals such as Li, K, Na, and Ca. The Sarysu River is about 800 km long and is formed by the confluence of the small rivers Jaman Sarysu, Jaksy Sarysu, Atasu, Taldisai, Kurmanak, Taldymanak, Kumdyespe, and Karakengir. The Sarysu River passes through volcano-plutonic formations of intermediate to felsic composition, sometimes with increased alkalinity, of the continental-margin Devonian volcanic-plutonic belt. The Shu River originates in the Tian Shan mountain range and flows along the western edge of the Shu-Ile Mountains. The products of mechanical erosion, particularly chemical weathering, accumulate in the path of the river's flow, forming large alluvial deposits in the Shu–Sarysu Depression (Figure 2).

During the Upper Cretaceous period within the Shu–Sarysu Depression, the climate exhibited variations ranging from tropical to savannah-like conditions, which supported the presence of river systems [10]. The spatial distribution of these rivers was largely influenced by active tectonic sutures. The accumulation of Cretaceous and Paleogene sediments is closely associated with the activity of ancient rivers and aligns territorially with their valleys. Underground saline waters in the Neogene deposits primarily flow toward areas where a lowering of groundwater is anticipated.

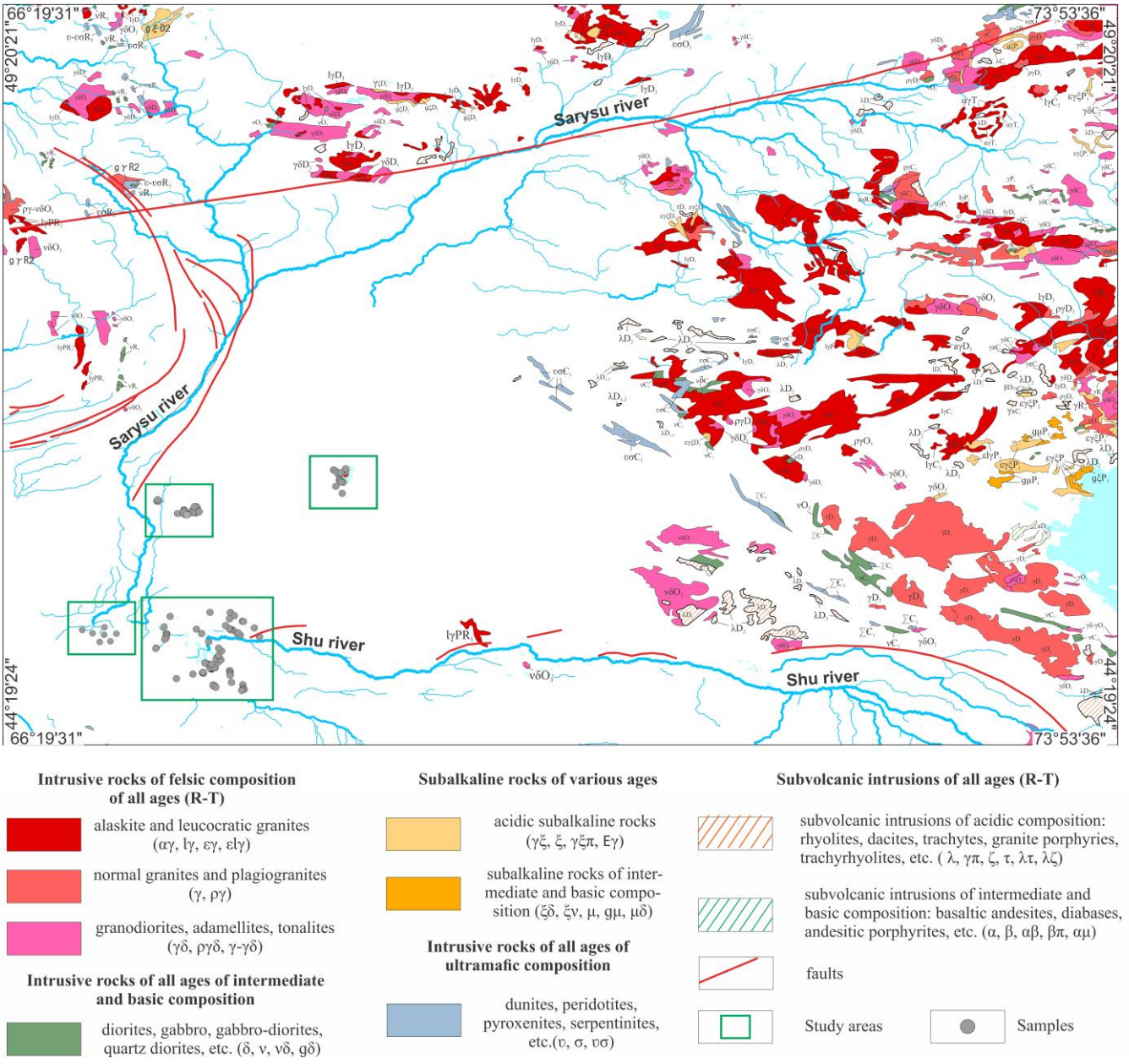

Figure 2. Hydrographic network of the rivers Shu and Sarysu, Scale 1:1,500,000 [12].

The Shu–Sarysu province, known for its rare-metal underground brines, shares its geographical boundaries with the corresponding tectonic depression. The most promising brines, enriched with microelements, are linked to the aquifer system found in Devonian and Carboniferous deposits, situated beneath loose Mesozoic–Cenozoic rocks at depths ranging from 1700 to 2900 m. Similarly, the Moyynkum region, also abundant in rare-metal waters, occupies the same depression, which was shaped by the presence of a thick layer of Middle-Upper Paleozoic deposits exceeding 900 m in thickness. Through testing wells located within specific oil and gas formations at depths between 874 and 2111 m, diverse brines with salinity levels ranging from 130 to 316 g per liter were discovered. Concentrations of rare elements vary over a very wide range (mg/L): potassium 660–2111, strontium 182–4800, iodine 5–40, bromine 31–2080, lithium 12–37.5 [7,10].

In the Neogene, aquifer systems at significant depths come into direct contact with felsic intrusions of the ridge, intersected by numerous disjunctive faults with a north-western strike. Through these faults, hydrocarbonate sodium waters infiltrate into the

Neogene aquifers and groundwater, even at significant depths (Figure 3). On the other hand, morphologically, this area represents an alluvial-lacustrine (deltaic) plain where the groundwater level is very close to the surface (ranging from 0.5 to 1 m). These groundwater sources undergo intense processes of evaporative salt concentration. There are numerous lake basins and salt flats where surface waters concentrate to form brines, and in shallow closed basins, even to the formation of self-precipitating salts.

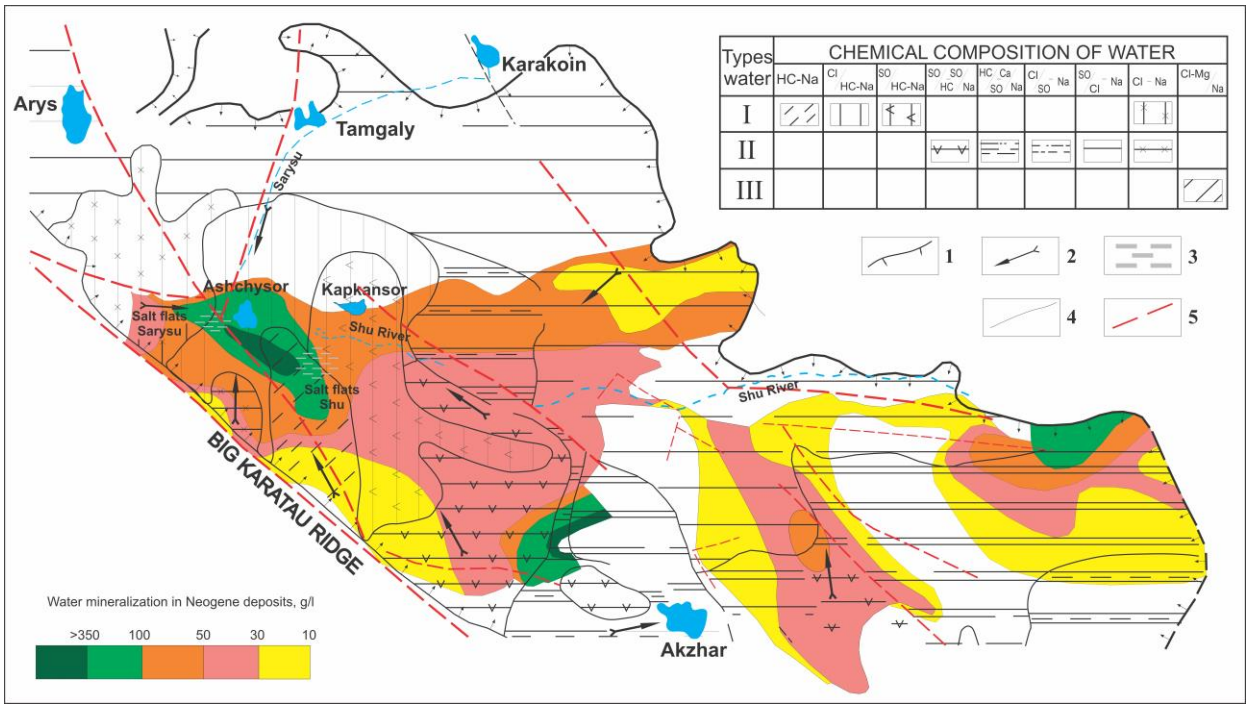

Figure 3. Hydrogeological Cross-Sections at the Junction Zones of the Shu and Sarysu Artesian Basins, illustrating Brine Discharge into the Overlying Aquifer of the Platform Cover [10]. 1—Contour of the distribution of the aquifer complex in Paleocene–Middle Eocene deposits; 2—direction of groundwater flow; 3—salt flats; 4—boundary of different types of groundwater; 5—tectonic faults.

3. Materials and Methods

The regional research method comprises two phases: the pre-field and field periods. During the pre-field phase, the study area's geomorphology, hydrogeology, and geochemistry were examined. Satellite images (multispectral and radar) from the Landsat-8, Maxar, Sentinel, and RADARSAT-1 satellites were previously downloaded from the website https://eos.com/landviewer/ accessed on 10 June 2023. These satellite images were interpreted to assess parameters such as water content, salinity, preliminary composition, and the geomorphology of saline brine deposits in the lower courses of the Shu and Sarysu, including the large salt flats Karakoin and Tamgaly. Interpretation of the Sentinel satellite images provided information regarding the content of water in salt flats, while the combination of Landsat and RADARSAT-1 images effectively revealed the geomorphological characteristics of the study region (Figure 4).

Subsequently, the field period involved geochemical sampling of saline brine deposits to assess lithium mineralization levels in salt lakes, salt flats, and salt domes. Geochemical surveys were conducted using both hydrogeochemical and lithochemical sampling techniques. The former method examines surface water composition to identify hydrogeochemical anomalies that indicate the presence of elevated lithium concentrations in shallow waters and brines, such as salt lakes, wet salt flats, and flowing wells. For sampling, a permanent layer of halite, including a temporary layer, approximately 10–15 cm thick, was initially exposed. Subsequently, a well with a diameter of 150 mm and a depth of 1 m was manually drilled into the silt layer. The brine was then allowed to settle in the well

for 5 min, after which a sample of brine was collected, and sediment was retrieved from the bottom of the well. The latter investigates the distribution of chemical elements in sediments and soils to identify halos that indicate the concentration of lithium beneath the surface.

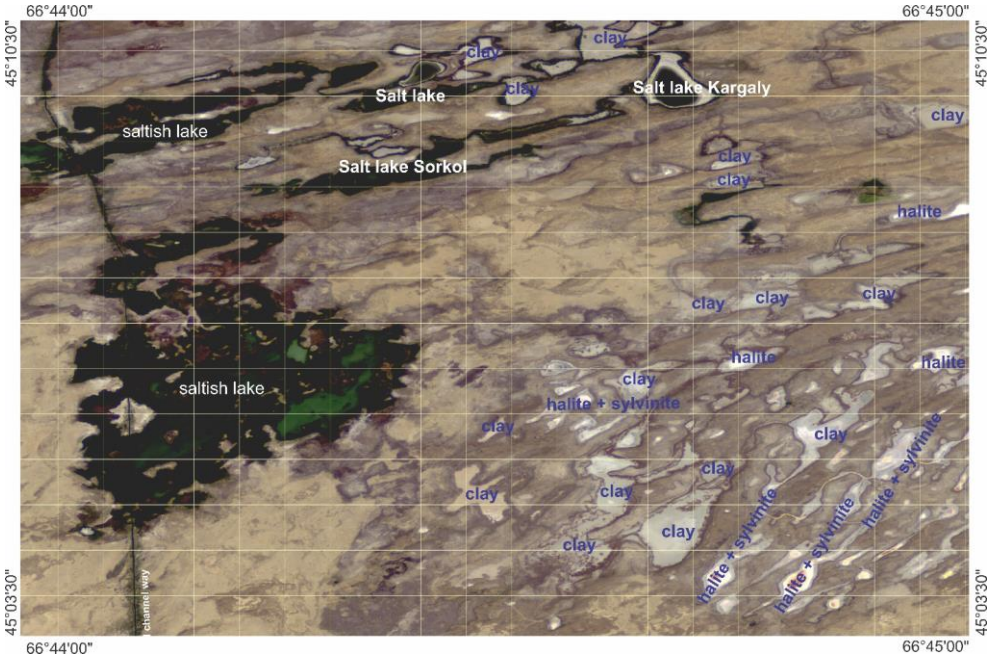

Figure 4. Preliminary Interpretation of the June 2022 Sentinel Satellite Image for the Lower courses of the Sarysu River (Base map from Google Earth).

During the field-work periods, manual drilling was employed for brine sampling, resulting in a total of 221 samples, including 166 brine samples and 47 soil samples collected from the bottom of the drill-hole.

In the lower course of the Sarysu River, numerous small sors (shallow salt flats) and salt flats are present, and samples of water and soil were collected from this area. The Sarysu Site covers approximately 90 square kilometers, and a total of 75 samples were collected (Figure 5).

The analysis involved quantifying the lithium levels in water (brine) samples obtained from the salt flats in the Shu–Sarysu depression. This assessment took place at the Chemical Laboratory of the Ahmedsafin Institute of Hydrogeology and Geoecology, utilizing the ICP-AES method. To ensure the quality of the analysis, 30 water (brine) samples were sent, along with soil samples, to the Chemical Laboratory of the Scientific Analytical Center (Almaty, Kazakhstan) (Tables 1 and 2).

Table 1. Table of statistical data for processing the results of analytical studies for lithium in liquid samples of field seasons 2022–2023.

Name	Number of Samples	Average (mg/L)	Median (mg/L)	Min (mg/L)	Max (mg/L)	Standard Deviation (mg/L)	Abnormal (mg/L)
Lower Sarysu sors	86	14.9	8.5	0.064	97.24	17.8	60.552
Lower Shu sors	37	3.316	3.37	0.03	6.75	1.861	8.952
Ashysor	22	2.783	2.574	0.912	4.76	1.167	6.075
Karakoin	20	5.129	4.058	1.05	14.478	3.525	14.632
Tamgaly	27	1.690	1.574	0.73	4.504	0.706	3.691
Aktuz	5	0.664	0.704	0.28	0.964	0.253	1.462

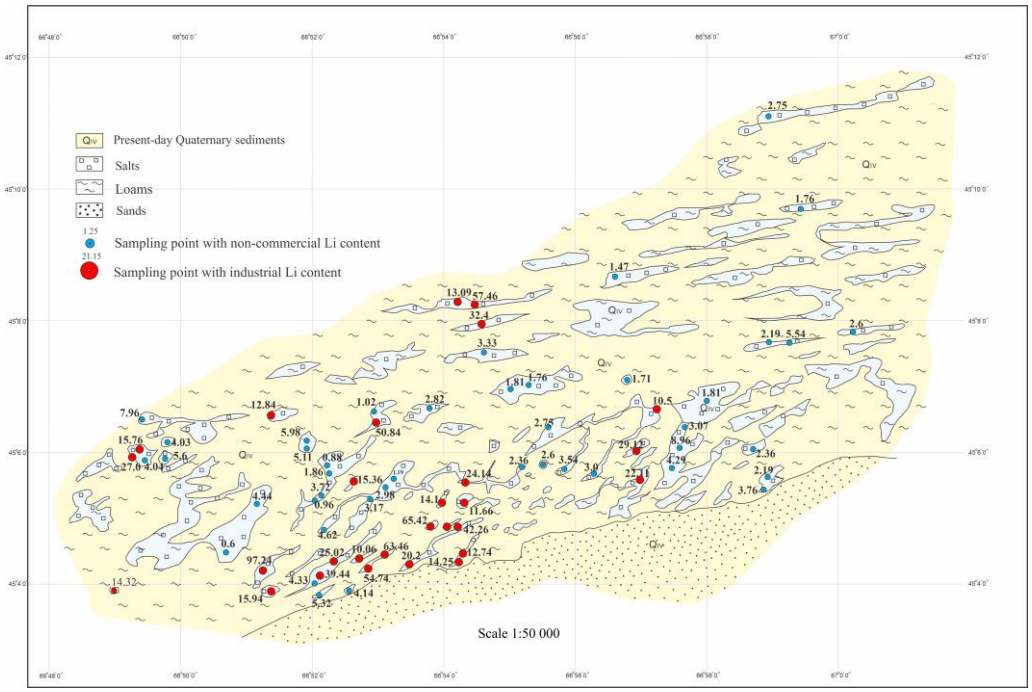

Figure 5. Salt flats sampling in lower course of the Sarysu River—1:50,000 Scale.

Table 2. Table of statistical data for processing the results of analytical studies for lithium in soil samples from field seasons 2022–2023.

Name	Number of Samples	Average (g/t)	Median (g/t)	Min (g/t)	Max (g/t)	Standard Deviation (g/t)	Abnormal (g/t)
Lower Sarysu sors	22	13.287	6.97	0.28	42.2	14.095	49.255
Lower Shu sors	65	18.706	18.5	1.636	40.5	9.557	47.170
Ashysor	14	8.049	5.74	1.97	35.2	8.317	30.691
Karakoin	9	7.209	7.4	3.14	11.02	2.807	15.820
Tamgaly	10	3.121	1.83	0.93	8.51	2.564	9.521
Kapkansor	23	13.034	14.2	2.8	23	5.546	30.839

Salt Lake Karakoyin (Figure 6A) is situated in the Ulytau district of the Karaganda region in Kazakhstan, located on the western border of the Betpak-Dala plateau. It covers an area of 72.5 km^2, and during periods of rainfall, the surface area can expand to 80–90 km^2. In the spring, with the snowmelt, the small Katagansai River feeds into the lake, but it typically dries up during the summer; 20 samples were collected from this site.

Salt lakes Tamgaly (Figure 6B) and Aktuz (Figure 6C) are located in the Turkistan region, covering areas of roughly 55 km^2 and 6 km^2, respectively; 27 samples were collected from Tamgaly site and 6 samples from Aktuz site.

Dry lake Telikol (Figure 6D) is situated in the Kyzylorda region and covers an area of approximately 25 km^2; nine samples were taken from this location.

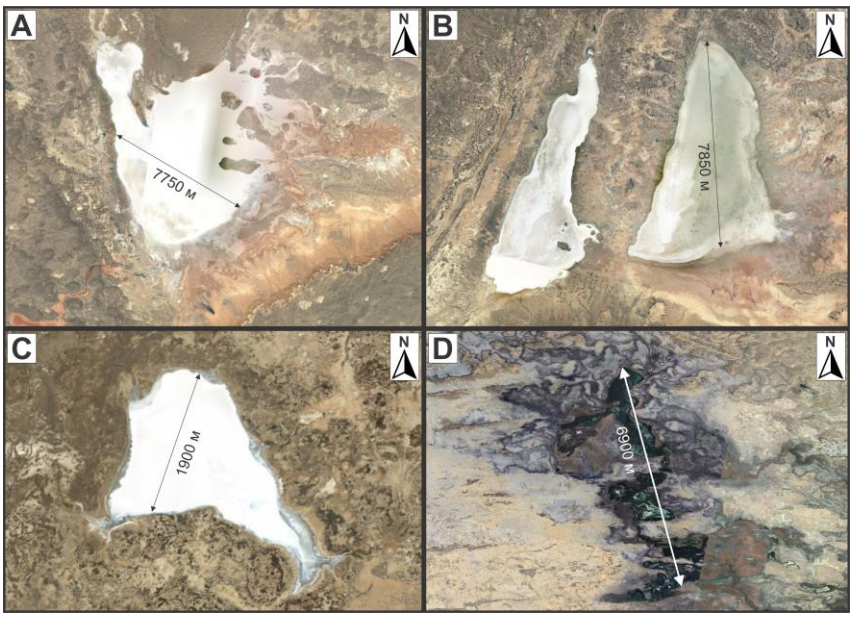

Figure 6. Salt flats sampling: (**A**)—Karakoin, (**B**)—Tamgaly, (**C**)—Aktuz, (**D**)—Telikol (base map from Google Earth).

4. Results

The initial research phase focused on investigating salt flats and salt lakes in the Shu–Sarysu Drainage Basin. Field research involving sample collection was conducted on saline brine deposits located in the lower courses of the Sarysu and Shu rivers, which encompassed notable salt lakes like Karakoin, Tamgaly, and Aktuz.

The salt lakes such as Karakoin, Tamgaly, and Aktuz are covered by a halite crust approximately one meter thick, with the presence of brine. In contrast, the salt flats in the lower courses of the Sarysu River are characterized by a thinner halite crust, the presence of sylvinites, and takyrs (cracked saline soil). Regarding the large salt flat Ashykol, situated in the lower courses of the Boktykaryn stream, it is completely devoid of water.

The Sarysu River originates from the Kazakh Usak Shokysy (small hills), and during dry years, it can disappear into the sand before reaching the Telikol-Ashykol depression. Some of its tributaries include Jaman Sarysu, Jaksy Sarysu, Atasu, Taldisai, Kurmanak, Taldymanak, Kumdyespe, and Karakengir. The river's primary source of water comes from snowmelt, with 96.6% of its annual flow occurring in April and May, 3.1% in autumn, and 0.3% in winter. It freezes in December and thaws in late March, with its width varying from 15 to 20 m in the upper course to 40 to 60 m in the middle and 150 to 200 m at the mouth. The valley is narrow in the upper course, and the riverbed and banks consist of sedimentary rocks made up of sand and gravel. Vegetation in the area includes desert plants like wormwood, fescue, and sedge, with a predominance of desert landscape near the river mouth.

Brine samples were collected from wells in the Amangeldy gas reservoir in 2022, situated 170 km north of Taraz city. An asymmetric brachianticline fold, with a steeper southeastern edge, is present at the top of the Upper Tournaisian–Lower Viséan productive layers, measuring 7 × 3 km. The structure at the top of the Lower Permian productive layer appears as a northeast-oriented brachianticline, measuring 13.5 × 7 km with an amplitude of around 400 m. Commercial gas content is associated with deposits from the Upper Tournaisian, Lower Viséan, Lower Serpukhovian, and Lower Permian. The reservoir operates under elastic-gas pressure.

The reservoir waters from Lower Carboniferous productive layers exhibit chloride–sodium–calcium and calcium–sodium compositions, with a salinity reaching up to 317 g/L. They contain significant concentrations of potassium, lithium, rubidium, cesium, strontium,

bromine, and iodine. Meanwhile, waters from the Lower Permian complex are classified as chloride-sodium, with a salinity level of 258.5 g/L.

As per the laboratory findings from the Akhmedsafin Institute of Hydrogeology and Geoecology, within co-produced formation brines exhibiting salinity levels between 99.5 and 131.5 g/L, the concentrations of trace elements are as follows, in mg/L: lithium—20.5–25.2 and strontium—188.7–237.1.

5. Discussion

For the Shu–Sarysu drainage basin, the results from the analysis of the salt flats suggest that the most promising area for lithium is the salt brine deposits in the lower course of the Sarysu River. This observation provides support for the theory of dissolved alkali metals migrating along the Sarysu River and precipitating in its downstream regions, where extensive and numerous salt flats have developed. Furthermore, this area experiences additional input of near-surface water from underground aquifers through fractures, further elevating the mineralization levels. The potential horizons for the distribution of lithium brines are within the Neogene-Quaternary deposits, with a thickness ranging from 15 to 30 m.

Table 1 displays the varying lithium (Li) concentrations in the six locations studied. In the Tamgaly, Aktuz, Telekol, and Ashysor salt flats, not a single sample with a Li content equal to or greater than the minimum industrial values found in known deposits (5 mg/L) was identified (Figure 7) [13]. Meanwhile, in the Karakoin salt flats, Lower Sarysu sors, and Lower Shu sors, the percentage of samples containing lithium concentrations exceeding 5 mg/L amounts to 23%, 51.5%, and 11.8%, respectively, relative to the total number of samples collected from these salt flats. Notably, with higher lithium content, the Karakoin salt flat and the Lower Sarysu sors are of particular interest. Within samples collected from these salt flats, the concentration of lithium ranges from 10 mg/L to 60 mg/L, occasionally even reaching as high as 97.24 mg/L. The average lithium concentrations in the examined saline brine deposits of the Shu–Sarysu drainage are as follows: Karakoin—5.13 mg/L, Tamgaly—1.7 mg/L, Aktuz—0.66 mg/L, Telikol—0.91 mg/L, Sarysu—14.1 mg/L, Ashysor—2.9 mg/L, and Shu—2.6 mg/L. In addition, there are soil samples with lithium concentrations exceeding 5 mg/L, namely 77.7% in Karakoin, 55.5% in Ashysor, and 37.5% in Lower Sarysu sors, in proportion to the total number of samples taken from each salt flat (Table 2) (Figure 8). Overall, the lithium concentrations found in soil samples are lower than those in water (brine) samples are.

As previously noted, to ensure the quality control of the laboratory research results, 30 brine samples from the studied salt flats were sent to the chemical laboratory of the "Scientific-Analytical Center" in Almaty. These samples were analyzed using the ICP-MS method, and the lithium content in the brine samples was found to be 3.5 times higher than the results analyzed using the ICP-AES method at the "Institute of Hydrogeology" (Figure 9). The ICP-MS method typically provides higher accuracy due to its sensitivity and ability to correct for interferences, with an accuracy for lithium that can be within ±1–2%. On the other hand, the accuracy of the ICP-AES method usually ranges within ±2–5%, but it can be more affected by spectral interferences and matrix effects compared to ICP-MS. The accuracy limits of these methods do not explain such significant differences in results. Numerous factors could have influenced the results, including proper sample preparation, calibration, interferences, and corrections.

Similar discrepancies in the results of analytical studies were noted in previous works. Upon reviewing a large number of publications that provide a quantitative assessment of lithium content in brine or salt flat solutions [3,4,14–20], it becomes apparent that none of them specifies the characterization or the name of the laboratory analytical methods used.

The complete analysis reveals that the total mineralization in each brine sample falls in the range of 300–400 g/L (Table 3), which aligns with the mineralization levels observed in brines from deposits in the Andes, Tibet, Mongolia, and other regions [15,16,21–25].

Table 3. Results of chemical analysis of brine in the studied areas of the Shu–Sarysu depression.

Name	Minerali-zation, g/L	Na, g/L	K, g/L	Ca, g/L	Mg, g/L	Chlorides, g/L	Sulfates, g/L	Bromides, mg/L	Average Li Content, mg/L
Karakoin	372	108.4	22.5	0.8016	16.5	145.373	115.998		5.13
Tamgaly	322	118.4	0.64	0.2004	14.2	166.648	50.215		1.7
Telikol	356	111.1	1.8	0.802	21.4	148.919	105.205		3.39
Lower Sarysu sors	360	98.5	6.5	1.002	28.5	163.202	98.043	256	15
Ashysor	362	119.7	1.3	0.2004	14.47	184.376	76.146		2.75
Lower Shu sors	306	104.1	1.96	0.6012	17.2	170.193	43.629		2.57
Atacama (Chile)	<400	113.4	32.1	0.5	11.4	210.6			0.5–2
De Yuni (Bolivia)	400	105.2	24.2	0.5	16.6	190.5			0.8–2

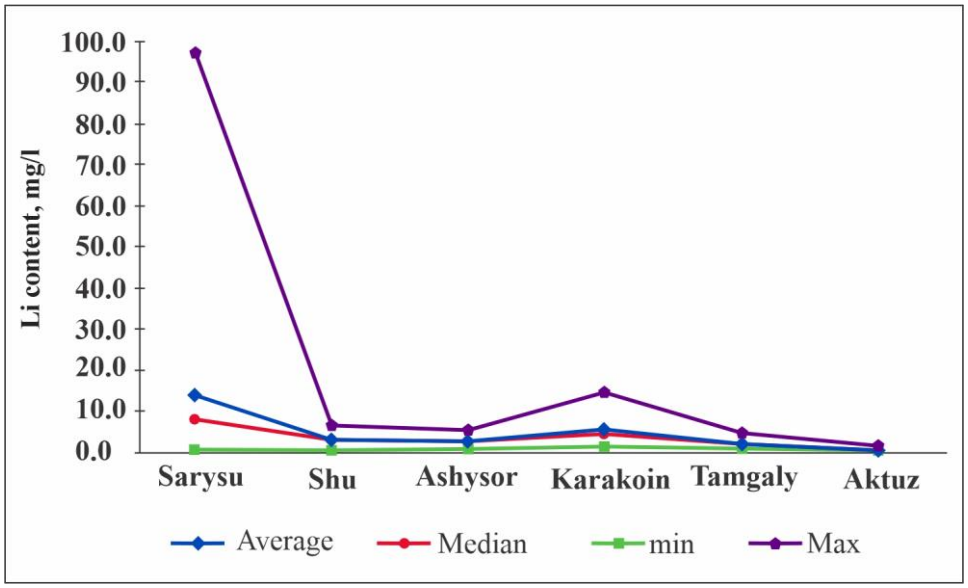

Figure 7. Diagram of statistical data processing of analytical research results on lithium in liquid samples of field seasons 2022–2023.

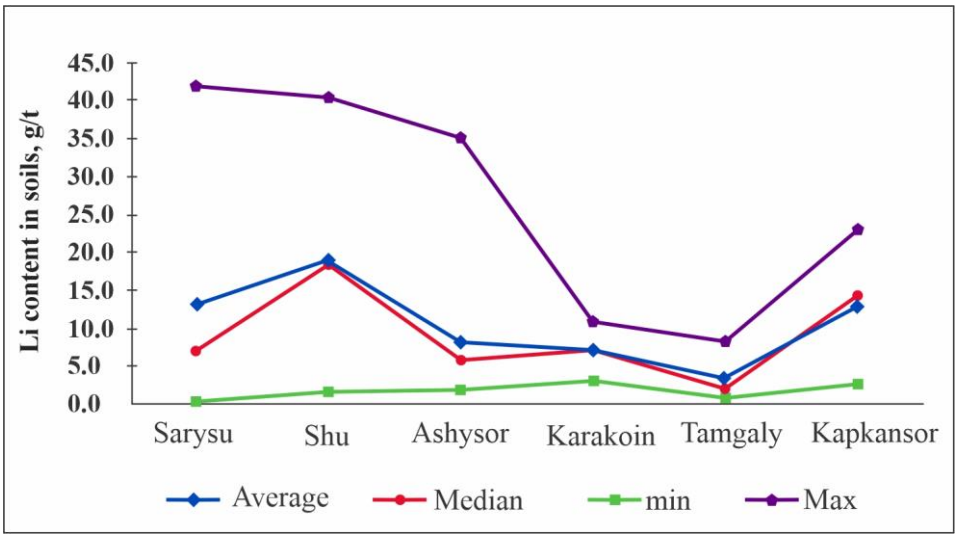

Figure 8. Diagram of statistical data processing of analytical research results on lithium in soil samples of field seasons 2022–2023.

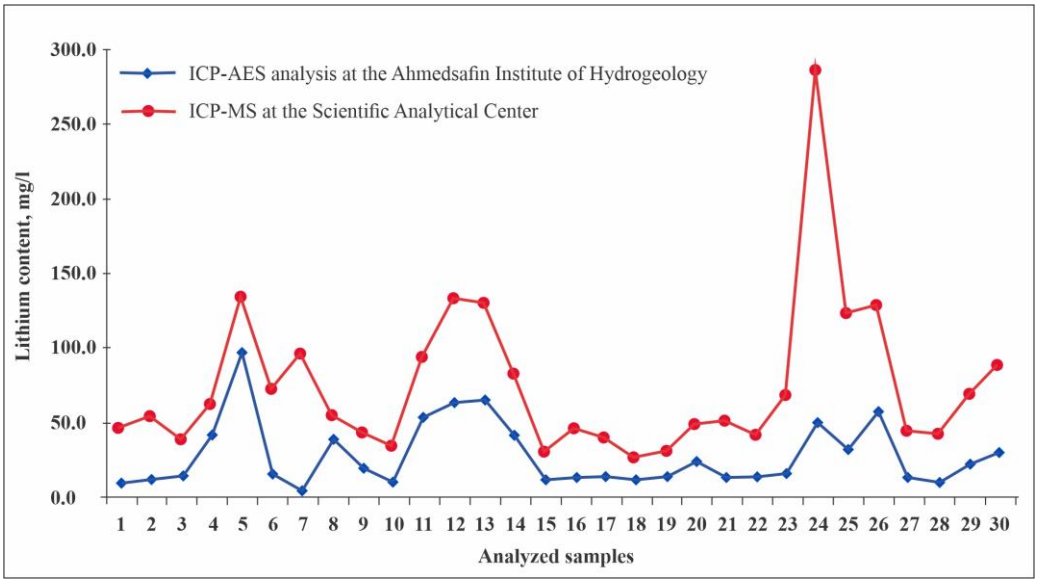

Figure 9. Lithium content comparison in brines detected by ICP-AES and ICP-MS.

The correlation of elements within mineralized waters of salt flats is depicted in the diagram (Figure 10). Analysis of the results from analytical studies indicates that there is no direct correlation between lithium content and the content of other elements. However, a careful analysis of the data in Table 3 reveals a weak correlation between the concentrations of Li and Mg, which nonetheless can be used as a relative exploration criterion [18,26,27].

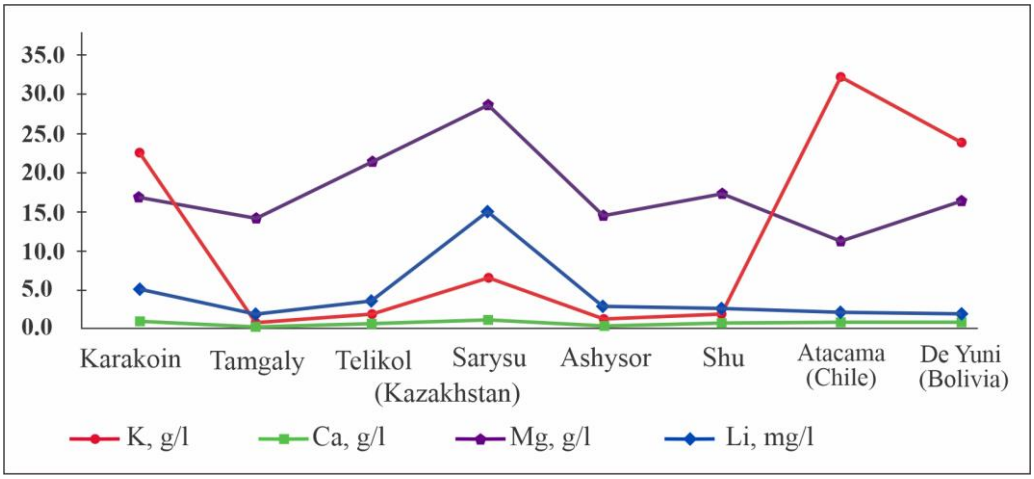

Figure 10. Concentrations of potassium, calcium, magnesium, and average lithium values in brines.

In the Sarysu salt flats area, the authors propose drilling several structural wells throughout the expansion zone to extract highly mineralized brines from deep layers and evaluate the lithium and other valuable components.

6. Conclusions

The main objective of the conducted research was to determine the lithium content in the sors of the lower reaches of the endorheic rivers Shu and Sarysu, with the aim of identifying a new geological-industrial type of lithium deposits as hydromineral raw materials. The obtained results clearly indicate the presence of Li in varying concentrations (from non-commercial to commercial) in all the studied sors, suggesting a high potential for lithium content in the sors of the Shu–Sarysu Depression. However, these data also show an extremely uneven distribution of Li in the investigated sors.

Despite the limited scope of the research on the salt flats of the endorheic rivers Shu and Sarysu, the unequivocal data obtained indicate that the most promising area for the localization of lithium mineralization in near-surface brine is the group of salt flats in the lower reaches of the Sarysu River. This fact supports the idea of the migration of dissolved alkali metals along the Sarysu River and their precipitation in its lower reaches, where extensive salt flats have formed. Additionally, in this area, there is supplementary recharge of near-surface waters by formation groundwater through faults, further increasing mineralization. The possible horizons for the spread of lithium brines are Neogene-Quaternary deposits, whose thickness varies between 15 and 30 m.

The higher lithium content in the group of sors in the lower reaches of the Sarysu River compared to other tested sors in the region may also be linked to the fact that, according to K.M. Akpambetova [11], underground brines in the aquifers of the Caspian Lowland, the Shu–Sarysu Depression, and most of Mangystau and Ustyurt are characterized by increased mineralization of 50–400 g/L. The undeniable potential of the sors in the lower reaches of the Sarysu River can be clearly judged by the scheme of lithium geochemical halos of these salt flats (Figure 11). The scheme clearly shows that, based on current knowledge, the most promising sors are in the western and southern parts of the studied area. Additional sampling is required in the anomalous areas to confirm the high Li concentrations. Areas with low Li concentrations require further sampling on a denser grid.

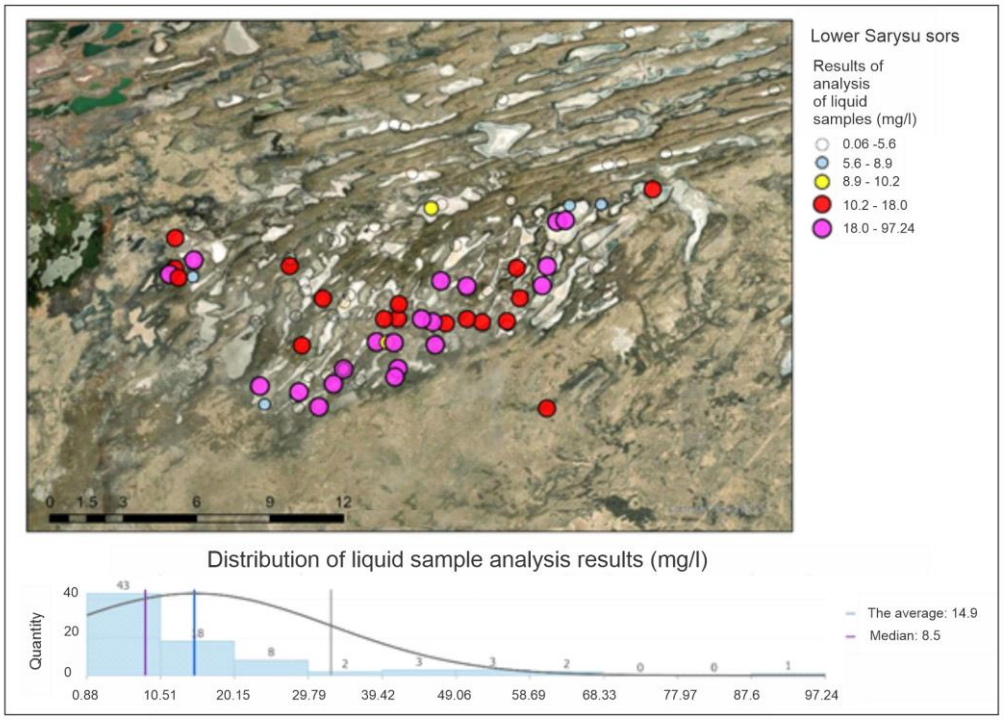

Figure 11. Satellite image with water sampling points in salt marshes in the lower reaches of the Sarysu River.

In addition to the significant prospects for lithium content in the group of sors in the lower reaches of the Sarysu River, it is also important to consider the presence of isolated high Li concentrations and the presence of lower but still notable Li concentrations in all samples from the sors in the lower reaches of the Shu River, which have been less studied compared to those of the Sarysu. Therefore, if additional work in the salt flats of the Shu reveals an increase in the number of samples with industrially significant Li concentrations (>10 mg/L), the productive Li area could amount to approximately 1800 km^2.

These data allow the authors to consider the Chu-Sarysu province as a whole to be promising for the identification of lithium-bearing salt flats. The areas with high and consistent Li concentrations in the samples from the salt flats in the lower reaches of the

Sarysu River are recommended for exploratory work. In conclusion, the authors would like to emphasize that the work on assessing the lithium content in the sors of western Kazakhstan should undoubtedly be continued to achieve the goal of identifying industrially significant lithium-bearing sors. The results of the authors' initial research fully justify the expansion of exploratory work in this direction.

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