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Hydrochemical Characterization and Suitability Assessment of Brackish Groundwater from 20 Wells in the Karauzyak District, Karakalpakstan

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Abstract

The Aral Sea crisis has led to severe degradation of surface water resources in the Republic of Karakalpakstan, elevating brackish groundwater as a vital alternative for domestic and agricultural water supply in this arid region. This study presents a comprehensive hydroecological assessment of groundwater quality in the Karauzyak district based on systematic sampling of 20 monitoring wells conducted in 2025. Groundwater mineralization ranged from 3.4 to 10.2 g/L, classifying most samples as brackish to highly brackish. The dominant hydrochemical facies were sodium-chloride and mixed sodium-sulfate-chloride types, as determined by Piper diagram analysis. Measured pH values varied between 7.1 and 8.3, while total hardness ranged from 6.5 to 26.5 mg-eq/L. Concentrations of potentially toxic trace elements (Pb, Cd, As, Hg, and others) remained below the maximum permissible limits of Uzbek SanPiN #0211-06 drinking water standards. However, elevated total dissolved solids (TDS), chloride, and sulfate levels significantly restrict direct use for drinking water and limit agricultural application without appropriate treatment. The results indicate strong influences of natural salinization processes, irrigation seepage from canals, and evaporative concentration under arid climatic conditions. These findings underscore the need for targeted desalination technologies, improved drainage systems, and expanded long-term monitoring networks to support sustainable groundwater management in the Aral Sea region.

1. Introduction

The Republic of Karakalpakstan, located in the lower Amu Darya basin within the Aral Sea region, is one of the most environmentally stressed territories of Central Asia. Long-term irrigation development, reduction of river discharge, climate aridization, and the desiccation of the Aral Sea have caused severe degradation of surface and groundwater resources. As a result, salinization, shallow groundwater rise, and deterioration of water quality have become major environmental and socio-economic problems in the region [1, 2].

Under these conditions, groundwater has become an important alternative source for drinking, agricultural, and technical water supply. However, groundwater quality in Karakalpakstan is strongly influenced by natural salinization, evaporation under arid climatic conditions, irrigation return flow, and water–rock interaction within sedimentary aquifers. Previous studies have reported increasing groundwater mineralization and hydrochemical transformation in irrigated areas of the Amu Darya basin [3, 4].

The Karauzyak district is located in the northern part of Karakalpakstan within the South Aral artesian basin and is characterized by complex hydrogeological conditions associated with Quaternary and Upper Cretaceous aquifers. Intensive irrigation, insufficient drainage systems, and secondary salinization processes have contributed to groundwater quality deterioration and rising groundwater levels. Despite the increasing dependence on groundwater resources in northern Karakalpakstan, recent site-specific hydrochemical assessments of the Karauzyak district remain limited.

The study area occupies approximately 5890 km² and includes irrigated agricultural lands vulnerable to salinization and waterlogging. The region has an arid continental climate with low annual precipitation and high evaporation rates, which significantly influence groundwater formation and salinity processes. Groundwater quality is additionally affected by anthropogenic factors, including agricultural return flow, mineral fertilizer application, and inadequate drainage infrastructure.

The present study aims to evaluate the hydroecological condition of brackish groundwater in the Karauzyak district (Fig. #1) using hydrochemical and hydrogeological analyses of 20 monitoring wells sampled during 2024–2025. The research focuses on groundwater mineralization, ionic composition, hydrochemical facies, and salinization processes, as well as groundwater suitability for drinking and irrigation purposes. Particular attention is given to the influence of geological strata, irrigation return flow, evaporation, and drainage conditions on groundwater evolution in the arid environment of the Aral Sea region.

Groundwater quality problems in the study region are associated with both natural and anthropogenic factors. Naturally occurring processes include mineral dissolution and elevated concentrations of certain trace elements [5], while human-induced impacts are mainly related to secondary salinization resulting from irrigation activities and groundwater-table rise [6]. These processes threaten aquifer sustainability and reduce the availability of high-quality freshwater resources in Karakalpakstan.

The Republic of Karakalpakstan occupies approximately 38% of the territory of Uzbekistan and is located in the lower reaches of the Amu Darya River near the former Aral Sea shoreline. The Karauzyak district covers an area of 5890 km² and includes extensive irrigated agricultural land. The study area is characterized by an arid continental climate with low precipitation and high evaporation rates, which strongly influence groundwater mineralization and salinity processes.

The objectives of this study were:

1. to characterize the chemical composition and hydrochemical facies of groundwater in 20 wells of the Karauzyak district;
2. to evaluate groundwater suitability for drinking and irrigation purposes according to national standards; and
3. to discuss groundwater salinization processes and management implications under the environmental conditions of the Aral Sea crisis region.

A total of 20 wells were sampled across different hydrogeological profiles. Groundwater analyses included organoleptic parameters (odor, color), general hydrochemical indicators (pH, hardness, mineralization, oxidizability), and specific components such as metal ions, nitrates, fluorides, and microbiological indicators in accordance with SanPiN standards. The hydrochemical characteristics of groundwater in Upper Cretaceous and Neogene–Quaternary deposits of the South Aral artesian basin were evaluated to determine groundwater suitability for domestic, agricultural, and technical use [21].

Novelty of the Study

This study provides a comprehensive hydroecological assessment of brackish groundwater in the Karauzyak district based on recent field investigations and analyses of 20 monitoring wells. The research integrates hydrochemical, hydrogeological, and environmental data, including groundwater mineralization, ionic composition, hydrochemical facies, groundwater dynamics, and salinization factors. Piper diagram analysis identified dominant Ca–HCO_3, mixed, and Na–Cl hydrochemical facies associated with evaporation, irrigation return flow, and water–rock interaction in Quaternary and Upper Cretaceous aquifers. The study also identifies aquifer intervals potentially suitable for limited agricultural and technical use despite elevated salinity. The findings provide a scientific basis for groundwater monitoring, desalination, irrigation optimization, and drainage improvement in the Aral Sea region.

Scientific Contribution of the Study

This research advances understanding of groundwater systems in arid regions by providing updated hydrochemical data for brackish groundwater in the Karauzyak district under modern climatic and anthropogenic conditions. The study identifies relationships between groundwater salinity, hydrochemical facies, irrigation return flow, evaporation, and aquifer interaction within Upper Cretaceous and Neogene–Quaternary deposits of the South Aral artesian basin. It provides a hydroecological classification of groundwater suitability for domestic and agricultural use and highlights the environmental impacts of secondary salinization and shallow groundwater rise. The results contribute new monitoring data for regional groundwater management, hydrogeological modeling, desalination planning, and sustainable water-resource development in the Aral Sea region and other arid irrigated environments.

Study location

The Republic of Karakalpakstan is the largest region of Uzbekistan, occupying approximately 38% of the country's total territory. Its population is over 2 million. It is located in the northwest of the Republic of Uzbekistan, in the central part of Central Asia. Territory of the Karauzyak district is 5890 sq. km and the border length is 530.1 km. For agricultural sown areas account for 32,397.0 hectares, including 32,397.0 hectares of irrigated land. Ehe population of the Karauzyak district is 52,700 people, of which 15,900 are urban residents and 36,800 are rural residents.

Geographical location and borders: Karakalpakstan is located in the lower reaches of the Amu Darya River and on the southern coast of the Aral Sea. Land use in Karakalpakstan is characterized by challenging natural conditions and an environmental crisis associated with the drying up of the Aral Sea. The region is adapting to water shortages and soil degradation through the introduction of new agricultural practices and sustainable resource management.

The geopolitical region of Central Asia is characterized by a continental arid and semiarid climate with mean annual precipitation of 600–800 mm in the mountainous areas and 80–150 mm in the desert regions [8]. The specific climatic conditions of Central Asia determine the crucial role that water plays in urbanization, supporting life, and preserving unique natural objects [9]. With the impacts of global warming and the increased demands for food and energy due to rapid population growth throughout Central Asia, the water resources in this region are facing increasing pressure [10]. Therefore, the scarcity of water and the uneven spatial distribution of water resources greatly limit the socio-economic development of the Central Asian region [11]. In addition to the scarcity of water resources, water pollwellution and corresponding water-related health problems are growing problems throughout Central Asia [12]. Several studies have reported the excessive salinity of the water downstream of the Amu Darya and Syr Darya rivers and described the sources of pollutants discharged into surface water [13, 14, 15].

In the areas in which water runoff disperses, which include most of Kazakhstan, Turkmenistan and Uzbekistan, almost all local and foreign scholars have identified two main problems: rising levels of water salinity and desertification coincident with land salinization [16, 17, 18]. More- over, the storage of toxic and radioactive substances has become a potential environmental problem associated with water resources in surface runoff catchment areas, mainly in the territories of Kyrgyzstan and Tajikistan, and in the foothills of Kazakhstan and Uzbekistan [19, 20].

In addition, the water environment of Central Asia has been greatly impacted by the use of mineral fertilizers and pesticides in agriculture and by the operations of mining, chemical production and other industries related to the utilization and storage of many harmful sub- stances [14, 15]. Accordingly, the dilapidation of industrial and urban sewage systems and treatment facilities is a considerable concern in regard to water quality [12]. Furthermore, the distribution of environmental pollution sources has changed; for example, in cities, domestic waste is retained in leaky landfills, the discharge of which has become a major factor in the pollution of brackish groundwater and river ecosystems.

To assess the groundwater and surface water resources of the Karauzyak district, it is necessary to first study the area from the perspective of the hydrogeological development of the region as a whole. This includes the geological structure, hydrogeological conditions, and identification of productive aquifers in the study area.

A total of 20 wells were sampled (Table #1) across various hydrogeological profiles. When studying the chemical composition of groundwater from the wells, we analyzed organoleptic (odor, color), general (pH, hardness, mineralization, oxidizability), and specific parameters (metal ions, nitrates, fluorides, microbiology) in accordance with SanPiN standards to assess its safety and suitability for drinking water, often using spectroscopic methods to accurately determine the elemental composition. The characteristics of groundwater in Upper Cretaceous and Neogene-Quaternary deposits of the South Aral artesian basin were studied. Data on groundwater mineralization are presented, and their suitability for various purposes is assessed. The article typically highlights the importance of such analyses, research methods, and interpretation of the results in the context of modern standards. (Table of sample analyses from the Tuyamuyin Vodokanal laboratory) [21].

Table №1

Number of wells in the Republic of Karakalpakstan

№	Name of districts	Total number of surveyed wells	Including							Number of water users	Groundwater withdrawal, thousand m^3/day
			Active			No active					
Total			Based on the availability of permits		Total	According to the technical condition of the well					
Certificated	No certificated	Reserve	Abandoned	Non-working							
1	Amudarya district	**56**	**29**	22	7	**27**	0	0	27	25	0.55
2	Beruniy district	**159**	**100**	25	75	**59**	3	0	56	15	6.50
3	Kanlykol district	**11**	**4**	2	2	**7**	2	0	5	4	0.22
4	Karauzyak district	**65**	**24**	1	23	**41**	0	12	29	45	0.64
5	Kegeyli district	**116**	**46**	26	20	**70**	21	24	25	28	71.60
6	Kungrad district	**208**	**10**	0	10	**198**	2	0	196	26	0.11
7	Muynak district	**50**	**1**	0	1	**49**	2	0	47	1	0.03
8	Nukus district	**99**	**45**	45	0	**54**	34	0	20	9	39.60
9	Takhtakupir district	**205**	**99**	34	65	**106**	13	10	83	87	10.08
10	Turtkul district	**118**	**70**	27	43	**48**	0	0	48	28	3.17
11	Khodjeyli district	**100**	**42**	37	5	**58**	6	0	52	13	3.61
12	Shimbay district	**208**	**98**	54	44	**110**	35	20	55	44	17.69
13	Shumanay district	**11**	**6**	0	6	**5**	2	0	3	4	0.90
14	Ellikqala district	**64**	**56**	28	28	**8**	0	0	8	41	2.32
	Total for the republic:	**1470**	**630**	**301**	**329**	**840**	**120**	**66**	**654**	**370**	**156.85**

Table #2

Groundwater coordinates and names at the Karauzyak district

№ п/п	Observation post	Wells №	Location	Coordinates		Drilled year	Depth	Filter installation, m	Диаметр, мм
1	97	97	Baq awil	41°34'39,9842"	60°54'53,9744"	2018	15	12–14	168
2	1	3	Esim ozek	43°06'47,3900"	60°03'32,0600"	2018	30	27–29	127
3	1	1	Qaramoyin	43°09'53,00"	60°03'38,90"	1997	10	7.50-9.0	168
4	1	2	Ko'rimli	43°13'20,4862"	60°02'53,70,78"	1997	20	17.50–19	127
5	60	60	Well 60	43°01'53,5"	60°01'23,0"	2018	14	11–13	100
6	26	426	Well 26/426	43°01'37,15"	60°01'17,44"	1963	9	7–8.0	100
7	26	426a	Well 26/426a	43°01'37,15"	60°01'17,44"	1963	7,2	4.7–6.20	100
8	88	88	Well 88	43°01'45,4"	60°00'38,1"	2018	12	9–11	100
9	98	98	Well 98	43°01'53,9"	60°00'32,83"	2018	12	9–11	100
10	99	99	Well 99	43°01'07,2"	60°00'39,9"	2018	15	12–14	100
11	100	100	Well 100	43°01'34,9"	60°01'58,6"	2018	15	12–14	100
12	86	660	S.Kamalov (Alisher awil)	42°55'07,18"	59°56'35,83"	1976	10	8–9	168
13	86	661	S.Kamalov (Oraqbai awil)	42°57'31,34"	60°59'39,51"	1976	10	7.5-9.0	159
14	17	478	Samat awil	43°10'18,9200"	60°01'36,3400"	1964	30	27.5–29.0	159
15	17	479	Mechet qasi	43°12'41,5055"	60°02'52,4535"	1964	21	18.5–20.0	219
16	283	358	Tauiq ferma	43°13'04,4035"	60°01'44,3594"	1990	40	38.50–39.20	168
17	283	359	Ferma Well 1	43°02'34,1077"	60°02'55,9734"	1990	21	17.50–19.0	168
18	283	360	Ferma Well 2	43°02'35,4254"	60°02'59,5690"	1990	15	12.50–14.20	127
19	1	1	Shariwa awil Well 1	43°12'29,1300"	60°02'55,9734"	2014	20	17.50–19	168
20	2	2	Shariwa awil Well 2	43°12'28,1209"	60°01'46,8308"	2014	7	4.50-6.0	168

Table #3

Chemical analysis data of the Karauzyak district

№	Name of wells	Smell	Aftertaste	Turbidity	Ammonia (NH_4^+)	(NO_2^-)	(NO_3^-)	Oxidizability	Sulfates (SO_4^{-2})	Total mineralization (dry residue)	Total ferrum (Fe^{+2} and Fe^{+3})	Copper (Cu^{+2})
1	Baq awil	0	2	1.3	1.27	0.02	0.0	4.1	705.6	2970	0.04	0.04
2	Esim ozek	0	2	0.2	0.9	0.0	0.0	2.3	508.8	2190	0.06	0.00
3	Qaramoyin	2	2	0.5	0.13	0.03	0.0	2.6	537.6	2250	0.00	0.00
4	Ko'rimli	0	2	0.8	1.1	0.02	0.0	3.4	494.4	2900	0.06	0.00
5	Well 60	1	2	0.2	1.0	0.06	2.55	5.5	302.4	2960	0.00	1.18
6	Well 26/426	1	2	0.7	1.5	0.0	1.76	3.3	936.0	4800	0.12	5.76
7	Well 26/426a	1	2	0.0	1.5	0.02	0.79	5.4	724.8	3520	0.00	3.78
8	Well 88	2	2	1.1	1.5	0.01	7.04	2.2	432.0	3430	0.12	3.00
9	Well 98	2	0	2.2	0.02	0.07	5.41	1.1	220.8	1010	0.10	3.44
10	Well 99	0	2	0.8	1.5	0.01	1.18	1.6	643.2	3800	0.08	3.20
11	Well 100	1	2	0.7	1.5	0.01	0.35	1.7	355.2	2240	0.06	0.74
12	S.Kamalov (Alisher awil)	0	2	0.3	0.71	0.01	0.0	2.2	499.2	2100	0.00	0.00
13	S.Kamalov (Oraqbai awil)	1	2	0.2	0.41	0.01	0.0	3.4	460.8	2350	0.04	0.00
14	Samat awil	1	2	0.7	1.15	0.02	0.0	3.0	590.4	2350	0.06	0.00
15	Mechet qasi	1	1	1.1	1.26	0.0	0.0	3.6	508.8	2580	0.06	0.00
16	Tauiq ferma	2	2	0.7	1.1	0.07	0.0	4.0	566.4	3010	0.04	0.00
17	Ferma Well 1	2	1	0.7	0.4	0.01	0.0	2.7	504.0	1980	0.10	0.00
18	Ferma Well 2	0	1	0.9	0.2	0.01	0.44	3.0	336.0	2120	0.04	0.00
19	Shariwa awil Well 1	0	2	0.9	1.1	0.02	0.0	4.2	480.0	2640	0.04	0.04
20	Shariwa awil Well 2	2	2	1.0	1.26	0.04	0.0	4.4	504.0	2690	0.02	0.00

2. Materials and Methods

2.1. Key Characteristics of Groundwater

The Karauzyak district is located in the northern part of Karakalpakstan (on the right bank of the Amu Darya River) and is considered an irrigated area with typical desert conditions. Key parameters based on long-term observations (including 2025–2026). Groundwater table **#3** (long-term fluctuations, average long-term level, and intra-annual changes). Study of mineralization (salinity) and chemical composition.

Problems and environmental conditions

The rise in groundwater levels is one of the fastest in Karakalpakstan, leading to secondary soil salinization and the formation of solonchaks. High mineralization makes the water unsuitable for drinking without desalination and limits its use in agriculture. Impact of irrigation: Seepage from canals (Tash-Arna, Kok-Ozek, etc.) and poor drainage raise the water level and increase salinity. In rural areas, many residents depend on groundwater (up to 70% in some villages), which creates health risks.

2.2. Water sampling

A total of 20 groundwater (Table #3) samples were collected from Karauzyak district wells between 2024 and 2025. The pH was determined using 780 pH Meter, and the total dissolved solids (TDS) values of the groundwater samples were calculated using ion concentrations. Sampling and laboratory results are

compared with the State Standards of the Water for drinking water [10]. Trends regarding the chemical composition are evaluated in terms of hydrogeology, arid climate, industrial and agricultural land use, and related distribution of contaminant sources.

Type of Wells: Primarily observation/monitoring wells used for water quality sampling and level measurements. Some appear to be production or existing operational wells (e.g., from Tuyamuyin Vodokanal or local supply), as flow rates (0.2–13 l/s) and specific capacities were tested. Dedicated monitoring points were used for consistent chemical and physical parameter collection.

Distance from Rivers/Canals: The Karauzyak district is on the right bank of the Amu Darya River, with strong influence from irrigation seepage (canals like Tash-Arna, Kok-Ozek). Wells were placed to capture recharge from surface water bodies and irrigation systems, as well as regional background conditions. Proximity to canals contributes to secondary salinization and mixing — many wells are in irrigated agricultural zones rather than far from surface water influences.

Monitoring includes: Depth (wells, observation points), sampling for mineralization, chemical composition (dry residue, chlorides, etc.), and frequency (seasonal/monthly at key sites).

In 2025, monitoring wells in the area were monitored for sustainable management.

The objects of study were groundwater from wells in the Karauzyak district. For the study in 2024 and 2025, water samples were collected for chemical composition analysis from 20 wells in the Karauzyak district (Fig. 2) in accordance with established standards [22] in clean, 1000 cm^3 polymer containers. The containers were completely filled with water and sealed with lids to eliminate air. The sample was not preserved and was analyzed as soon as possible after collection, but no later than 24 hours [23].

2.3. Chemical analysis

The laboratory methods used are listed in Table #4 [11]. General requirements for methods for determining oil products in natural and wastewater are defined according to [2] and details are provided in Supplementary Materials, Section S1. All samples were taken from the water intake nearest the wellhead for general chemical analysis. In the course of early studies at the sites of oil deposits and near oil product plants, traces of oil products were found in groundwater, which indicates that the groundwater is not sufficiently protected during the extraction and processing of oil and gas [1]. This part of the sampling campaign is a follow-up to evaluate whether or not petroleum contamination was still a problem [24].

Table #4

Laboratory method details used for water testing [27, 28]

Parameters	Detection limits (mg/l)	Instruments	Description of methods
Dry residues, total solids		OHAUS Adventurer Balance	Gravimetry (0.00001 g)
pH		Mettler Toledo pH meter	Potentiometry
Ammonia	0.1	Photocolorimeter	Photometric method for ammonia and ammonium ions (in total) with Nessler reagent calibration from 0.1 to 3.0 mg/L.
Nitrite	0.003	Photocolorimeter KFK-2	Photometric method for nitrites using sulfanilic acid. Calibration range from 0.003 to 0.3 mg/L.
Nitrate content using sodium salicylic acid	0.1	Photocolorimeter	Photometric method for determining the nitrate using sodium salicylic acid. Calibration range from 0.1 to 2.0 mg/L.
Ferrum (iron)	0.01–0.03	Photocolorimeter	Photometric method in an alkaline medium with sulfosalicylic acid to form a yellow-colored complex (400–430 nm). Calibration range is 0.10–2.00 mg/L [11].
Metals: Cd, Co, Mn, Cu, As, Ni, Hg, Pb, Cr, Zn	0.00001	Atomic Emission Plasma Spectrophotometer.	ICPE-9820 Atomic Emission Plasma Spectrophotometer. Calibration range is 0.00001–10.0.
Alkalinity CO3, HCO3	10	Automatic titrator	Titration: HCl volume consumption per 100 mL sample using phenolphthalein indicator
Ca, Mg	10	Automatic titrator	Titration: consumption of Triton B per 100 mL sample using an indicator.
Chloride	10	Automatic titrator	Titration: mercurimetry by Hg(NO3)2 per 50 mL sample and indicator.
Sulfate	30	OHAUS Adventurer Balance	Gravimetric method using precipitation of sulfate ions in a hydrochloric acid medium with barium chloride. Range is 30–300 mg/L [12].

Quantitative chemical analysis of the collected water samples was carried out in the Central Chemical and Bacteriological Laboratory of JSC “Karakalpak Suv Taminot”.

Chemical and physicochemical analysis of the water samples (Fig. #3) was conducted immediately after sampling using standard methods. Temperature, transparency, and odor measurements were conducted in accordance with the guidelines [25]. A TM 10 – 3 thermometer with a measurement range of -5 to + 40°C and a measurement error of ± 0.2°C was used to measure water and air temperature [26].

To study the chemical composition, water samples were collected monthly from wells in the Karauzyak district throughout 2025. It was found that the groundwater temperature in the studied wells remains virtually constant throughout the year, averaging 4–7°C. Aquifers located deep underground are little affected by seasonal temperature changes. Water and soil analyses were also conducted in the Karauzyak district, where the geological and lithological structure and hydrochemical composition of groundwater in the chalk aquifer complex were clarified, with the aim of identifying areas of low-mineralized groundwater distribution that are of interest for their practical use for the development of livestock farming and small-oasis irrigation of lands [27].

Results and discussions

Groundwater mineralization within the Karauzyak district ranges from 0.5–2.5 g/L and above. Groundwater mineralization in wells drilled into Upper Cretaceous aquifers (K_2) of the YUPAB, confined to clayey sandstones, ranges from 1.4 to 62.5 g/L. The aquifer penetration depth in the study areas ranges from 300 to 700 meters.

During the research, the groundwater mineralization of the aquifer within the Karauzyaksky district was determined based on the results of analysis of selected samples and ranges from 3.4 g/L to 10.2 g/L. The water is classified as sodium chloride. Its relatively low values are explained by the inconsistency of the impermeable layers separating the Lower and Upper Cretaceous aquifers and the presence of filtration windows in the sedimentary section through which low-mineralized Upper Cretaceous waters mix with the saline waters of the Lower Cretaceous. Based on the ion-chemical composition, the waters studied by the wells belong to the sodium chloride class, classified as brackish and highly saline. The concentration of hydrogen ions (pH) varies from 7.10 to 8.30, and the oxidizability is 2.15–5.85. Total hardness for all wells ranges from 6.5 to 26.5 mg-eq/l.

Currently, the surface water mineralization is approximately 0.9–1.2 g/L in the upper reaches and 1.5–2.0 g/L in the lower reaches of the Syrdarya. These numbers indicate that water mineralization has increased by two to three times compared with the pre-1940 levels. Currently, the ion composition of the river water is dominated by SO_4^{2-}, Na + and K+, and high concentrations of Cl− have been observed in the lower reaches of the SDR [31].

The Aral Sea basin is a dynamic hydrological system characterized by an arid climate that receives an inflow of river water with high seasonal and interannual variability [32]. In particular, the spatial dynamics of the groundwater levels and salinity in the Khorezm region of Uzbekistan show that the groundwater in the western and southern parts of this region is particularly shallow and saline [33]. In the Amudarya delta there is a distinct contrast in salinity between the low-salinity river water (~ 1 g/L) and the high-salinity unconfined groundwater (10–95 g/L) [34]. The Aral Sea is currently shrinking, which affects groundwater discharge; this discharge manifest as changes in the groundwater levels and salinization. Thus, shallow groundwater with predominantly moderate salinity is likely to contribute to the increase in soil salinization. Due to the effects of intensive irrigation, the groundwater in the middle and lower reaches of the Zarafshan River is no longer suitable for drinking. The highest mineralization and SO_4^{2-} contents have been recorded in the lower reaches of the Zarafshan River, where the maximum concentrations of SO_4^{2-} reach 6.1–12.0 times the MAC [35]. However, both groundwater and soil salinity have improved slightly in recent years.

Piezometric groundwater levels were established at the ground surface or at a depth of 0.5–4.5 m; self-discharge with a flow rate of 6.0 l/s was observed in only one well #46. The well flow rate during pumping was 0.2–13.3 l/s with drawdowns of 10.4–11.8 m, specific flow rates were 0.02–1.13 l/s·m. The filtration coefficient varies from 0.12 to 7.47 m/day, averaging 0.64 m/day, the water yield coefficient - from 15.8 to 156 m2/day, averaging 75 m2/day. Due to high mineralization and low pressure, the tapped aquifers cannot be recommended for irrigation. Other technical uses of this groundwater are possible with further research [36].

The study area is located at the boundary of two large first-order hydrogeological structures: the Ustyurt artesian basin to the west and the Syr-Darya artesian basin to the east. The boundary between them is the Aral-Kyzylkum swell, a powerful linear structure that represents a regional divide between the two basins. The swell itself is the interface between second-order structures—the North Ustyurt and South Aral artesian basins, which comprise the study area. The geological structure of the YUPAB is distinguished by a folded basement composed of highly dislocated and metamorphosed sedimentary and igneous rocks of Paleozoic age and a loose sedimentary cover of Mesozoic-Cenozoic deposits [37].

The lower reaches of the ADR and SDR in the Aral Sea basin, which includes UZ, eastern TM, and southern KZ, face severe surface water and groundwater pollution and land salinization due to agricultural activities [28]. In particular, agricultural irrigation and production processes are the main cause of water pollution in the middle and lower reaches of the ADR and affect the ionic compositions from the upstream to the downstream areas [29]. Overall, the available surface water in the Navoi region (S3) is characterized by significant mineralization. This mineralization occurs because the southern part of this region currently exhibits intensive agricultural irrigation and above-average fertilizer use, which leads to significant soil and groundwater salinization [30]. The upstream region of the Zarafshan River is composed pre-dominantly of calcium bicarbonate, while the downstream region has high levels of SO_4^{2-}, Cl^- and Mg [29].

The aquifers of the Karauyaz region are located in the Upper Cretaceous Cenomanian (K2) deposits.

Currently, four key groundwater deposits are identified in this region, which are of regional importance for water supply, agriculture, and potential industrial development (Fig. 4):

1. **Groundwater deposits of Karakalpakstan**. It encompasses the left-bank part of the lower Amu Darya River within the Republic of Karakalpakstan. It is characterized by a complex structure of aquifer systems, including both unconfined alluvial horizons and confined (artesian) horizons of deeper

Neogene-Quaternary deposits. A significant portion of the reserves is subject to secondary salinization as a result of rising groundwater levels and capillary rise of salts.

2. **Groundwater deposits of the Lower Amu Darya** Groundwater Deposit is located on the right bank of the lower reaches of the Amu Darya River (primarily within the Khorezm region and southeastern Karakalpakstan). It is composed primarily of highly permeable alluvial aquifers. The deposits are formed through seepage losses from the riverbed and irrigation systems, resulting in a close hydraulic connection with surface water.
3. **Groundwater deposits of the South Aralsea**. Located in the southern Aral Sea region, within the influence zone of the shrinking Aral Sea, the field is characterized by the presence of several pressurized (artesian) complexes in Neogene-Quaternary sediments. Artesian waters exhibit increased mineralization as they approach the former sea basin, but in some areas, horizons of acceptable quality for domestic and drinking water supply remain. Reserves are formed primarily through lateral filtration from the recharge area in the south and southeast.
4. **Groundwater deposits of the Ustyurt Plateau**. It is located on the Ustyurt Plateau (northern Karakalpakstan). Aquifers are represented primarily by fracture-vein and fracture-pore systems in Paleogene-Neogene carbonate-terrigenous sediments. Brackish and slightly brackish waters occur as localized lenses and zones of active water exchange in the upper part of the section; below, highly mineralized brines predominate. The field is of great importance as a potential source of industrial and drinking water for the development of gas condensate fields and the plateau's infrastructure [37]

These deposits represent the primary source of decentralized water supply in the northwestern region of Uzbekistan, amidst the scarcity of surface water. However, their exploitation is associated with a number of hydrogeological and environmental risks: secondary salinization, reduced pressure in artesian aquifers, contamination by drainage runoff, and a general deterioration in groundwater quality in the Aral Sea region due to climate aridization and anthropogenic pressure.

Further rational use of these deposits requires comprehensive monitoring, modeling of the groundwater regime and the introduction of modern technologies for the protection and artificial replenishment of reserves [3, 38].

In the Republic of Karakalpakstan, the hydrogeological conditions of the lower reaches and delta of the Amu Darya River determine the special role of groundwater as an alternative and strategically important water supply source in the face of chronic surface runoff shortages and progressive degradation of river water quality.

Among the currently operating and prospective facilities, two major hydrogeological complexes, located on the right and left banks of the lower Amu Darya valley, are of particular importance:

The Right-Bank Groundwater Field of the Lower Amu Darya is located on the right bank of the river within the administrative boundaries of Karakalpakstan. Its primary source of recharge is seepage from the Amu Darya River bed and major main canals. Hydraulic connection with surface waters determines seasonal fluctuations in the groundwater level and chemical composition. Salinity in the active water exchange zone typically ranges from 0.5 to 1.5 g/dm³, classifying these waters as brackish or low-mineralized. The field is actively used for domestic and drinking water supply in populated areas and for industrial and technical needs.

The Left-Bank Groundwater Field of Karakalpakstan encompasses the left-bank part of the Amu Darya delta and lower reaches, including the Khodjeyli, Shumanay, Kungrad, Kanlykul, and parts of the Muynak districts. Aquifers are represented by a multilayered layer of Quaternary alluvial deposits (Fig. #5), dominated by sandy and sandy loam fractions, along the riverbed and large canals (Kegeyli, Kuanysh-Zharma, Oktyabr-Arna, etc.). Brackish and slightly brackish lenses form due to infiltration from surface watercourses; the thickness of brackish water lenses reaches 20–40 m and a width of 1–3 km. Artificial replenishment and local desalination are actively used in canal zones. Salinity varies from 0.6–1.2 g/dm³ in zones of intensive recharge to 3–5 g/dm³ and more in peripheral areas affected by collector-drainage runoff and secondary salinization.

Thus, the right-bank and left-bank groundwater deposits of the lower Amu Darya remain key elements of the decentralized water supply system of the Republic of Karakalpakstan. Their rational use requires comprehensive hydrogeological monitoring, mathematical modeling of the regime, the implementation of artificial replenishment technologies, and strict groundwater quality control under conditions of increasing anthropogenic and climatic stress in the Aral Sea region [39].

Groundwater in aquifers 10–40 meters thick, primarily associated with Quaternary and Neogene-Quaternary sand and sand-gravel deposits of alluvial and subaerial origin, is considered promising and actively exploited in the Republic of Karakalpakstan. These aquifers form local and extended brackish water and low-mineralized lenses in the valley and delta of the lower Amu Darya, as well as in the canal zones of the main irrigation systems.

Environmental monitoring of groundwater in the Republic of Karakalpakstan is being conducted as part of regional joint research in the Amu Darya Delta, where problems of soil salinization, rising groundwater levels, and land degradation due to intensive irrigation and the consequences of the Aral Sea crisis predominate.

In the Aral Sea region, the environmental situation makes the availability of high-quality drinking water problematic. Therefore, monitoring the qualitative and quantitative state of groundwater in the region is essential. The Karauzyak district, one of the northern regions of the Republic of Karakalpakstan, is one of the most acutely affected by water supply and farm development issues. To study the qualitative and quantitative state of groundwater in the study area, some field expeditions were conducted during the research period, exploring thermal and groundwater sources in the Karauzyak district.

The results of our research group's monitoring of the physical and chemical composition of groundwater in the Karauzyak district are presented in the following graphs.

Analysis of the plot points

The Piper diagram (Fig. 6) was used to classify the hydrochemical facies of groundwater samples collected from 20 monitoring wells in the Karauzyak district. This trilinear diagram facilitates the identification of dominant cation and anion types and the visualization of mixing and evolutionary processes.

Quantitative Classification of Hydrochemical Facies

Based on the relative percentages of major ions (meq/L), the samples were classified into the following hydrochemical facies (using standard criteria where one or more ions exceed 50% of total cations or anions, or mixed types when no single ion dominates > 50%):

- **Calcium-Bicarbonate (Ca-HCO_3) type** (dominant in ~ 55% of samples, e.g., Bag-aul, isolated Karauzyak #98, #99, #100, Korimli awil, Alisher awil): Ca^{2+} > 50% of cations (typically 60–85%); HCO_3^- > 50% of anions (often 55–75%). These represent relatively fresh to brackish waters with low to moderate mineralization (generally < 5 g/L).
- **Mixed Calcium-Sodium-Bicarbonate (Ca-Na-HCO_3) type** (~ 20% of samples, e.g., Karauzyak #60): Ca^{2+} (40–60%) and Na^++K^+ (30–50%) co-dominant; HCO_3^- dominant anion with subordinate Cl^- and SO_4^{2-}.
- **Sodium-Chloride (Na-Cl) type** (~ 15% of samples, e.g., Karamoyin): Na^++K^+ > 60–80% of cations; Cl^- > 50–70% of anions. These exhibit the highest mineralization (often > 6–10 g/L).
- **Mixed Sodium-Sulfate-Chloride (Na-SO_4-Cl) and Magnesium-Sulfate types** (remaining ~ 10%, e.g., Karauzyak #88, Yesim-ozek): Na^++K^+ and/or Mg^{2+} dominant cations with elevated SO_4^{2-} (30–60%) alongside Cl^-.

Most data points cluster in the lower left to central region of the diamond field, confirming a predominance of alkaline earth (Ca^{2+}+Mg^{2+}) over alkali (Na^++K^+) cations and weak acids (HCO_3^-) over strong acids (Cl^-+SO_4^{2-}) in the majority of samples.

Name of wells	Ca	Mg	Na	K	HCO3	Cl	SO4	F	Ca meq/L	Mg meq/L	Na meq/L	K meq/L
Karauzyak №60	5,4	0,575	40,7	29,4	16,2	40,5	43,3	1,1	0,269	0,047	1,770	0,752
Karauzyak №88	8,07	8,075	48,6	35,3	17,83	40,4	41,8	0,02	0,403	0,664	2,114	0,903
Bag-awil	9,25	6,607	48,7	35,4	10,24	38,8	50,9	0,01	0,462	0,544	2,118	0,905
Karauzyak single №98	11,2	0,797	48,7	35,4	24,71	30,9	44,4	0,01	0,559	0,066	2,118	0,905
Karauzyak single №99	9,39	0,669	52,1	37,9	10,36	39,3	50,4	0,02	0,469	0,055	2,266	0,969
Karauzyak single №100	8,74	0,874	52,4	38	24,03	27,3	48,7	0,03	0,436	0,072	2,279	0,972
Esim-ozek	77,7	33,1	13,8	10	8,61	69,5	21,8	0,3	3,877	2,724	0,600	0,256
Qaramoyin	77,7	1,6	11,9	8,7	18,58	38	43,4	0,01	3,877	0,132	0,518	0,223
Korimli awil	8,05	0,67	55	26	14,42	41,9	43,7	0,05	0,402	0,055	2,392	0,665
Alisher awil	7,94	0,66	61,00	30,00	15	42,40	43,00	0,04	0,396	0,054	2,653	0,767
Karauzyak single №26–426	**31,1**	**39,4**	**20**	**9**	**20,66**	**29,4**	**49,9**	**1,1**	**1,552**	**3,242**	**0,870**	**0,230**
Karauzyak single №26–426a	49,2	10,26	28	14	30,8	25,6	43,6	0,02	2,455	0,844	1,218	0,358
Oraqbay awil	24,4	21,66	35	19	11	43,1	45,9	0,01	1,218	1,782	1,522	0,486
Samat awil	19,9	5,1	48	23	7,8	29,2	63	0,01	0,993	0,420	2,088	0,588
Meshit qasi	23,8	32,8	28	15	8,9	36	55	0,02	1,188	2,699	1,218	0,384
Tawiq ferma	14,4	24,5	40	21	7,9	37,5	54,6	0,03	0,719	2,016	1,740	0,537
Ferma well №1	16,8	31,2	35	17	7,8	42,1	50,1	0,3	0,838	2,567	1,522	0,435
Ferma well №2	25,3	11	45	18	13,7	32,8	53,4	0,01	1,263	0,905	1,957	0,460
Shariwa awil well №1	14,2	40	30	15	9,1	36,7	54,1	0,05	0,709	3,292	1,305	0,384
Shariwa awil well №2	29,20	57,50	7,00	6,00	13	57,70	29,60	0,04	1,457	4,732	0,304	0,153

Links to Geological Strata, Processes, and Anthropogenic Influences

These facies reflect a combination of natural and anthropogenic controls characteristic of the South Aral artesian basin:

1. **Geological Strata Influence**: The Ca-HCO_3 facies is primarily associated with Upper Cretaceous (K_2) aquifers composed of clayey sandstones and carbonate-bearing sediments. Dissolution of carbonate minerals (calcite, dolomite) in these strata releases Ca^{2+} and HCO_3^-, especially in the 47–49 m interval identified as relatively promising. In contrast, Na-Cl and mixed Na-SO_4-Cl types show stronger influence from deeper Lower Cretaceous or Neogene-Quaternary layers containing evaporite minerals (halite, gypsum) or ancient saline horizons, facilitated by filtration windows allowing mixing between aquifers.
2. **Irrigation Return Flow and Drainage Influence**: Elevated Na^+, Cl^-, and SO_4^{2-} in wells such as #60, #88, and peripheral sites (e.g., Karamoyin) indicate significant contribution from irrigation seepage and collector-drainage return flows. Poor drainage efficiency in the Karauzyak district leads to evaporative concentration of salts from applied irrigation water (often already mineralized from the Amu Darya) and mobilization of soil salts. This is evident in the shift from Ca-HCO_3 toward Na-Cl along the Piper diamond, a classic signature of secondary salinization driven by intensive irrigation via canals such as Tash-Arna and Kok-Ozek.
3. **Evaporation and Arid Climate Effects**: The overall enrichment in Na^++K^+ and Cl^- relative to Ca^{2+} in more mineralized samples results from strong evaporative concentration under the hyper-arid climate (precipitation 80–150 mm/year). Shallow groundwater tables (0.5–4.5 m) promote capillary rise and salt accumulation, pushing points toward the Na-Cl apex. Long-term monitoring data (wells #60, #88, #97–#100) show stable to increasing mineralization trends correlated with seasonal evaporation peaks.
4. **Mixing Processes**: Intermediate positions (e.g., Karauzyak #60) indicate mixing between fresher recharge waters (Ca-HCO_3 from alluvial lenses or canal infiltration) and saline formation waters. Self-discharging wells and variable filtration coefficients (0.12–7.47 m/day) support active hydraulic connectivity.

Piper Diagram Interpretation Summary

The dominance of Ca-HCO_3 facies in Upper Cretaceous intervals suggests potential for limited agricultural use (salt-tolerant crops) after minimal treatment, while Na-Cl dominated samples require desalination for potable use. These patterns align with regional studies in the Aral Sea basin, where irrigation-induced salinization shifts hydrochemical evolution from bicarbonate to chloride-sulfate types.

The chemical composition of brackish groundwater is spatially variable because it depends in part on local geologic, hydrologic, and climatic conditions. Chemical variations in brackish groundwater are important because they can have implications for the feasibility, treatability, and associated cost of using brackish groundwater [40]. The national brackish groundwater assessment focused on defining the occurrence of brackish groundwater at depths less than 3,000 feet (ft) below land surface because few data were readily available below that depth. Groundwater- chemistry data for about 380,000 groundwater samples were compiled from 33 sources [41] for this assessment. In a preliminary compilation of brackish groundwater data in the United States, five water types accounted for the major-ion composition of 70% of samples. PHREEQC calculations indicate that 57–77% of samples were oversaturated with respect to barite, calcite, or chalcedony. In the study, 5–14% of samples had concentrations of arsenic, fluoride, nitrate, or uranium that exceeded drinking-water standards [42].

Recommendations and Prospects

To improve the ecological situation, the following is required:

- • Strengthening drainage and optimizing irrigation.
- • Expanding the monitoring network (including automated sensors).
- • Using drainage water after desalination.
- • Monitoring soil salinity in parallel with groundwater.

Water Classification	Mineralization / TDS Range (g/L)	Hydrochemical Characteristics	Suitability for Drinking	Suitability for Irrigation
Fresh water	< 1.0	Low salinity, acceptable chemical composition	Suitable	Suitable
Slightly brackish water	1.0–3.0	Moderate salinity increase	Limited suitability	Suitable for salt-tolerant crops
Brackish water	3.0–10.0	Elevated mineralization and dissolved salts	Generally unsuitable without treatment	Restricted use; risk of soil salinization
Very brackish water	10.0–35.0	High salinity and strong mineral accumulation	Unsuitable without desalination	Highly restricted; only under controlled conditions
Saline water	> 35.0	Extremely high salt concentration	Unsuitable	Unsuitable for most irrigation purposes

Conclusions

The measured groundwater quality parameters indicate that most sampled waters in the Karauzyak district do not satisfy recommended drinking-water standards without treatment. Total dissolved solids (TDS), represented by groundwater mineralization values of 3.4–10.2 g/L, substantially exceed the World Health Organization (WHO) and Uzbekistan drinking-water guideline values of 1.0 g/L for acceptable palatability and domestic supply. Waters exceeding 3 g/L are classified as highly mineralized brackish groundwater and are generally unsuitable for direct human consumption.

Groundwater hardness ranged from 6.5 to 26.5 mg-eq/L, significantly exceeding the commonly recommended drinking-water threshold of 7–10 mg-eq/L. Such elevated hardness is associated with high concentrations of calcium and magnesium ions and may cause scaling in water supply systems and reduced suitability for domestic use. The highest hardness values were observed in wells influenced by intensive evaporation and prolonged water–rock interaction within confined aquifers.

Chloride and sulfate concentrations also indicate substantial salinity problems. Sodium–chloride and sodium–sulfate hydrochemical facies dominate in several wells, especially Karamoyin and Karauzyak well #88. According to WHO and SanPiN recommendations, chloride concentrations above 250 mg/L and sulfate concentrations above 500 mg/L reduce drinking-water quality and may produce adverse taste and gastrointestinal effects. The elevated sulfate content observed in sulfate-rich facies likely reflects dissolution of gypsum-bearing sediments combined with irrigation return flow and drainage infiltration.

Nitrate and fluoride concentrations remained generally below maximum permissible concentrations during the study period, indicating limited contamination from agricultural nitrogen sources and fluorine-bearing minerals. Similarly, concentrations of toxic trace metals including Pb, Cd, As, Hg, Cr, Ni, Cu, and Zn remained below established drinking-water limits, suggesting that groundwater salinity rather than toxic-metal pollution represents the principal water-quality concern in the study area.

From an irrigation perspective, groundwater suitability is primarily restricted by high salinity and sodium content. Waters with TDS above 3 g/L and dominant Na–Cl facies present elevated risks of soil salinization, sodicity development, and reduction of soil permeability under long-term irrigation use. According to FAO irrigation-water classifications, most groundwater samples fall within high to very high salinity hazard categories, requiring strict drainage control and selective irrigation practices. However, moderately mineralized waters from several Upper Cretaceous aquifers at depths of approximately 470–490 m may be suitable for irrigation of salt-tolerant crops under controlled management and periodic soil leaching.

The systematic comparison with drinking-water and irrigation standards therefore demonstrates that:

most investigated groundwater requires desalination before domestic use;

sodium–chloride groundwater is unsuitable for conventional irrigation;

moderately mineralized groundwater may support limited agricultural application for salt-resistant crops;

toxic metals currently do not represent the major environmental risk; and

secondary salinization driven by irrigation return flow and evaporation remains the dominant hydroecological challenge in the Karauzyak district.These findings provide a scientific basis for rational utilization and protection of groundwater resources in arid territories of Karakalpakstan [45].

Declarations

Author Contribution

“Conceptualization, A.A. and D.S.; methodology, K.D.; software, F.E.; validation, K.D. and A.A.; formal analysis, S.M.; investigation, A.A.; resources, K.D.; data curation, A.A. and R.M. and A.Q; writing—original draft preparation, A.A. and D.S.; writing—review and editing, K.D.; visualization, D.S.; supervision, A.A.; project administration, A.A.; funding acquisition, A.A. All authors have read and agreed to the published version of the manuscript.”

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Figures



Figure 1

Karauzyak district location, scale 1:500 000 [25]

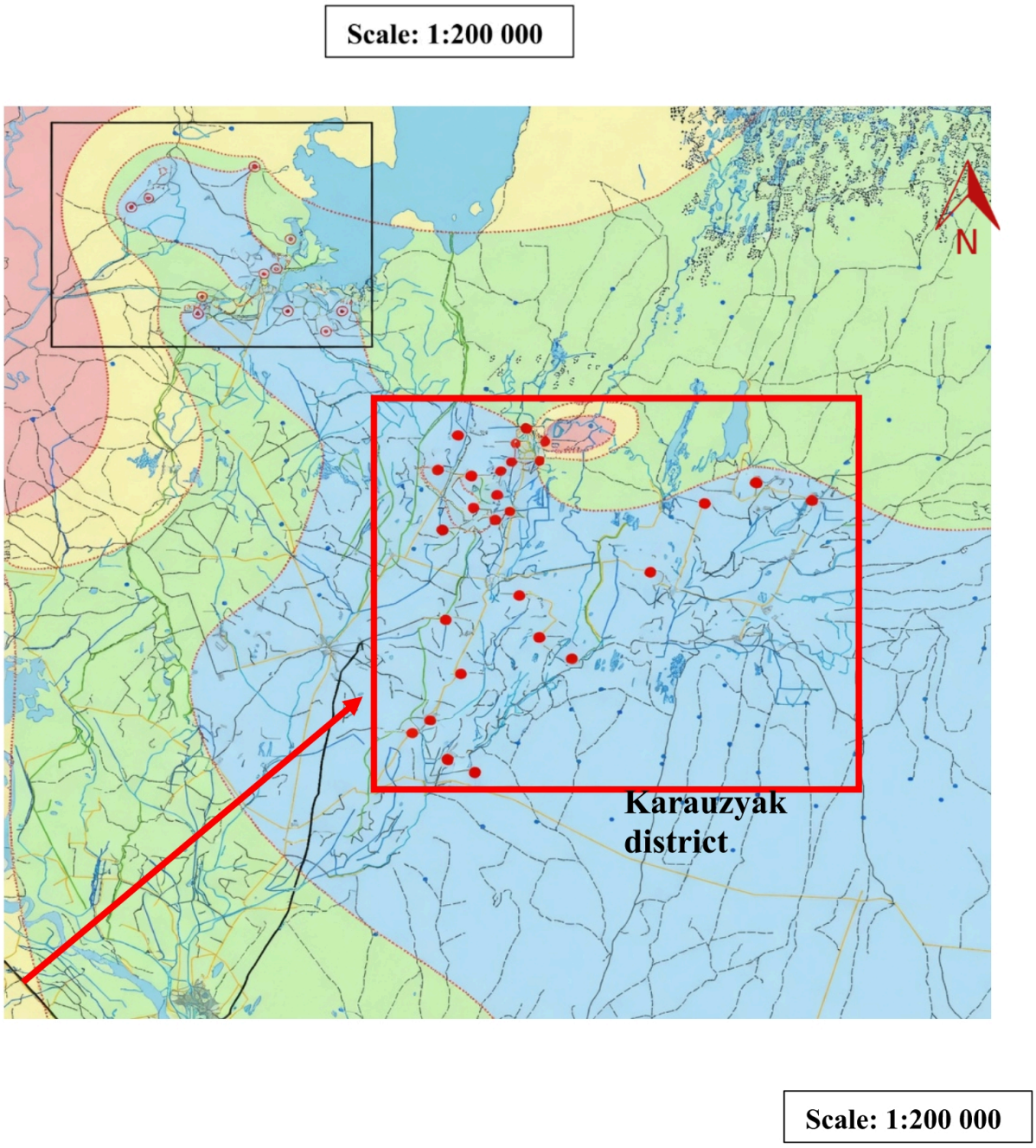


Figure 2

Map of wells in the Karauzyak district



Figure 3

Water sampling process.

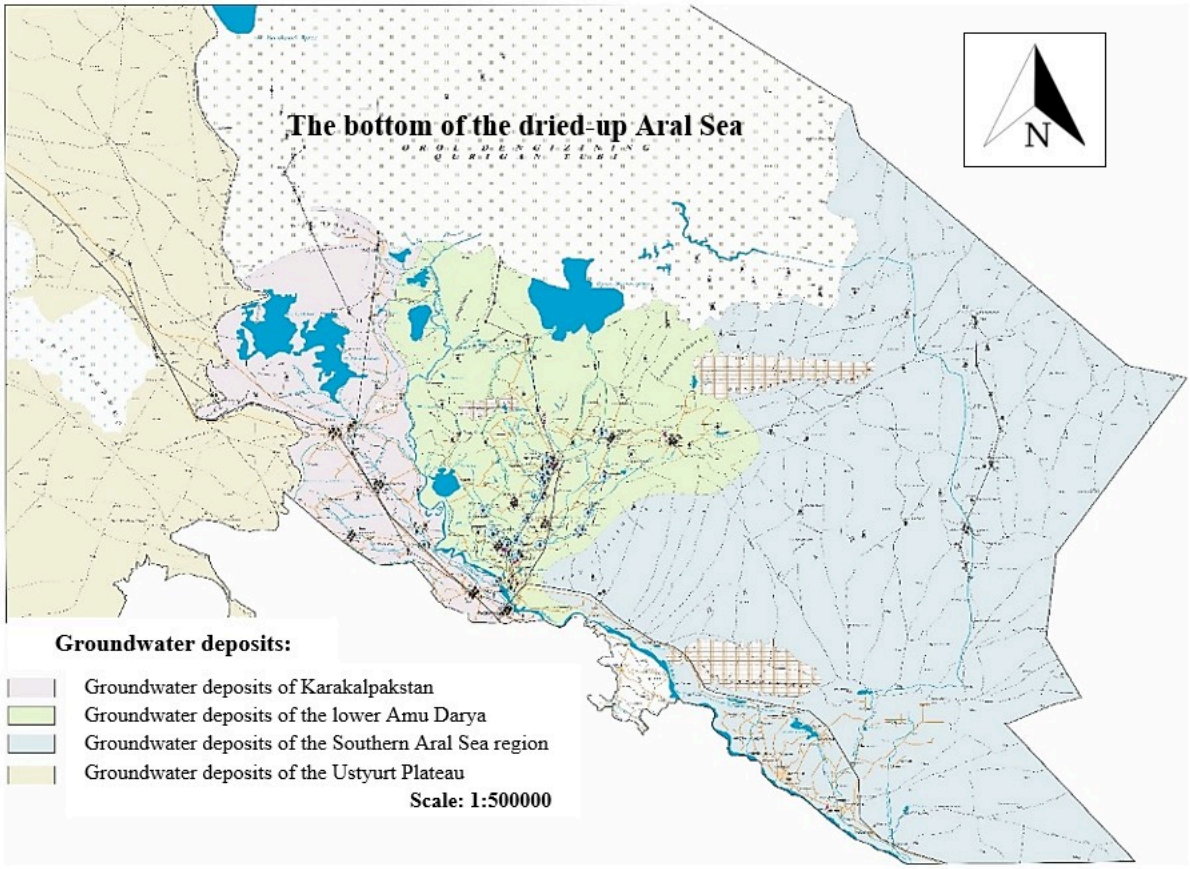
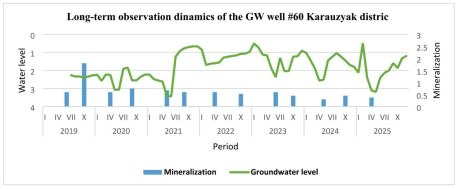
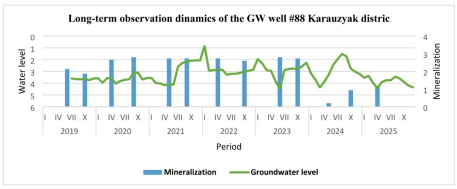
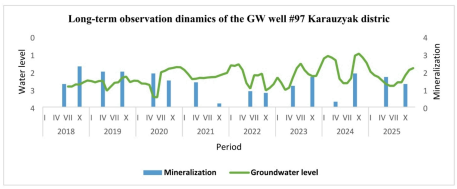


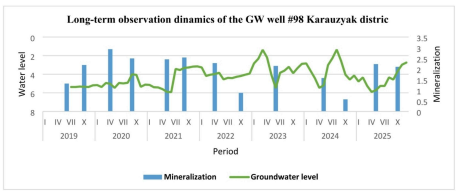
Figure 4

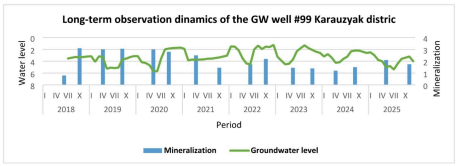
Map of groundwater deposits of the Republic of Karakalpakstan

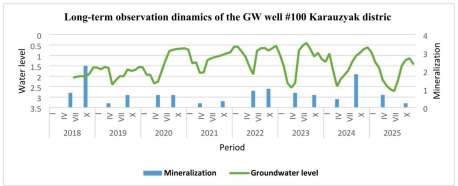












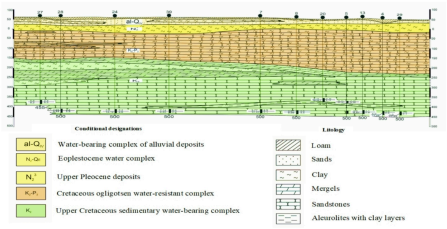


Figure 5

Hydrogeological section of the Karauzyak district

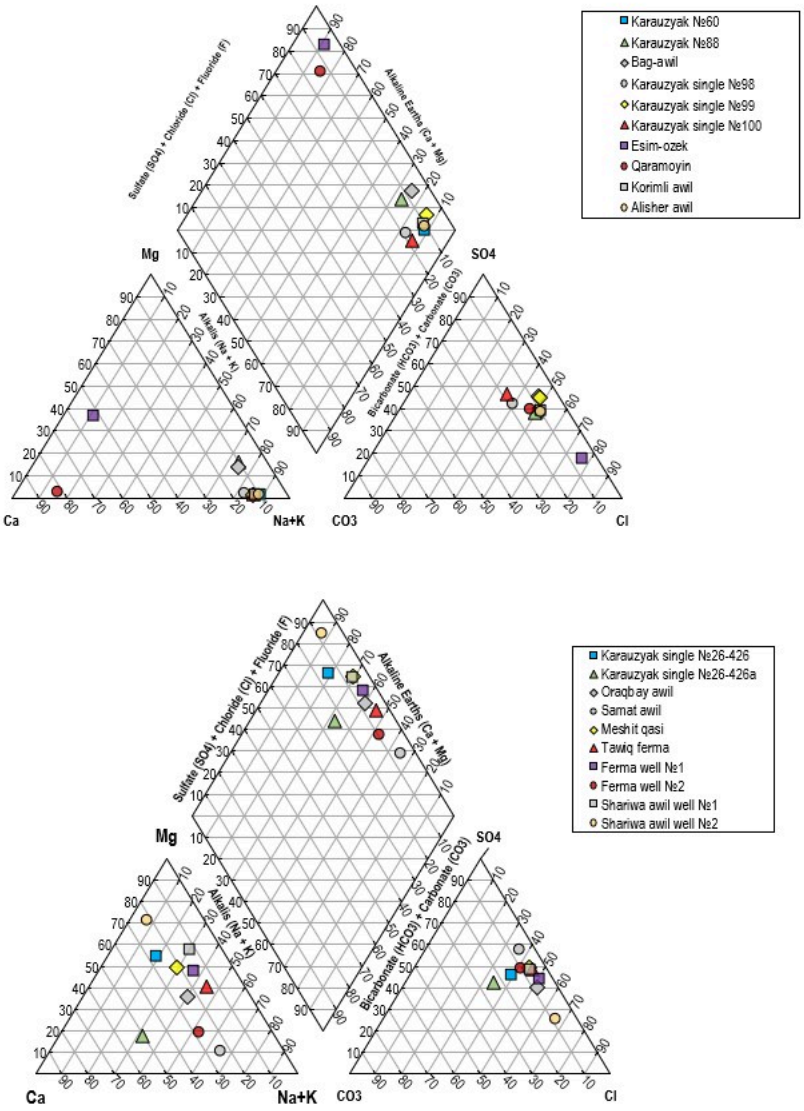


Figure 6

Piper plot of the ground water of Karauzyak district