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Assessing groundwater and soil quality in West Kazakhstan amid climate impacts and oil industry contamination risks

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Climate change from anthropogenic activities had resulted in devastating disruptions in Kazakhstan. This includes drought in 2023 and flooding in 2024, with widespread water pollution. The field surveys and water-soil sampling were carried out in 2013 to study West Kazakhstan's (WK) groundwater and soil. From this, preliminary classifications were made. The water was categorized into three groups: (1) potable household, (2) technical irrigation, and (3) unsuitable for use. WK is under intensive oil and gas exploration and processing activities, thus, groundwater in the region faces contamination risks. As a result, proper, permanent groundwater quality monitoring is needed. Along with these efforts, the groundwater and soil samples were collected and analyzed. This included measuring for different anions and cations concentration, hydrogen ions pH concentration, total dissolved salts (TDS), total water hardness C, sodium adsorption ratio (SAR), and sodium content (SC). The Piper and Durov Diagrams illustrate water-soil quality. The WK region was categorized into three groups by the water-soil quality outputs; the (1) group of the WK North-East region with the smallest salinity level, suitable for the household use; the (2) group of the WK South-East, suitable for irrigation, as technical water, which is unsuitable as the potable water and requires purifications for the household needs; the (3) group of the WK North-West, unsuitable for irrigation and high salt content, which requires substantial purification for the household or irrigation use. Among the salinity chemistry levels, the most common are chloride-sulfate, soda-sulfate, sulfate-soda by anions; next sodium and sodium-calcium by cations. Soda-saline lands were identified in some areas of the WK region. The upgrading of melioration for sufficient water quality improvement will require substantial efforts. The content of petroleum products in some soil samples significantly exceeds the maximum permissible concentration. A further, more detailed investigation is required with more permanent soil water monitoring efforts, especially following the recent flooding events.

Climate change due to worldwide anthropogenic activities have devastating consequences worldwide in many regions and countries. This includes Kazakhstan in the Central Asian (CA) region. Kazakhstan's water sustainability is a complicated issue that is impacted by water pollution, floods and droughts. This is worsened with inefficient water distribution systems throughout the country^{1–3}. The surface-groundwater interactions, water movement dynamics, water budget have permanently changed, influenced by changing nature, as climate, and intensive human disruptions, affected by various interconnected factors^{4–6}. These factors include soil penetration level, topography, climate, surface water recharge capacity, underground water aquifer system geological - hydrogeological conditions^{7–9}. Other factors include man-made disturbances to surface water. This includes engineering constructions like canals, dams, and reservoirs; the elimination of wetlands and swamps; and the disruption of natural discharge systems. All of these result in the depletion of groundwater resources^{10–12}. The groundwater reserves depend on natural geological-hydrogeological and physiographic factors, as well as human activities. Human activities include rate of water extraction, conditions of groundwater recharge, and groundwater restorations activities, such as managed aquifer recharge (MAR) support programs^{13–16}. With depletion of surface water resources, as is happening now in the CA countries, which destroyed the Aral Lake natural discharge system, the CA countries are intensifying the groundwater extractions, leading to aquifer depletion, especially in arid and semiarid climate regions^{17–19}. On a global scale, the highest groundwater

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extraction is in Asian countries, which account for 75% of the total global water volume. India, China, Pakistan, Iran, Indonesia, Bangladesh, Saudi Arabia, and Turkey are intensively depleting their groundwater resources. Globally, most extracted groundwater resources are used for agriculture. This is true in Asian countries, where agriculture accounts for approximately 76% of the total water consumption^{20–24}. CA countries have problems with the surface water resources, leading to intensifying groundwater extractions. The efficient use of groundwater resources is becoming critical^{25–28}. Groundwater extraction and the efficient use with connected aquifer restoration programs, such as MAR, is becoming very important²⁹. Localization of the groundwater extraction activities with MAR is getting more economically efficient. Since water is used at the intake site with connected MAR technologies, there is less investment required to build expensive water distribution networks with canals and pipeline systems for long distances. The proper groundwater monitoring, groundwater resources assessment programs are required in Kazakhstan. Sustainable groundwater leveling improves soil moisture, soil meliorative conditions, preventing soil salinization and balancing with efficient drainage swamp areas^{30,31}. Proper soil-water resources monitoring, investigations along with continued evaluations of irrigated farming conditions are required to expand in Kazakhstan. Climate change issues are important to consider in combination with increasing human disruptions of the environment, including engineering projects and agricultural programs, which are often unsustainable. This can be seen in the fate of CA's Aral Sea. Permanent water resource investigation programs need to be expanded in Kazakhstan. Proper water monitoring programs require substantial investment and government legislation support, which is missing in most CA countries. In such cases, even small water resources conditions investigation programs would be reasonable to set up in Kazakhstan. For efficient water resource management, it is critical to accurately classify water reserves into different categories, and include ratings based on water quality. In previous water-soil quality field investigations in Western Kazakhstan, three preliminary groups were developed. These three groups, include: (1) the lowest salinity level, which can be used with minimum purification efforts for the household use; (2) water suitable for irrigation, as water in the, as technical water, which is unsuitable as the potable water and requires purifications for the household needs; (3) water unsuitable for irrigation and household use, due to the high salt content, which requires substantial water purification investment. The water resources investigation efforts require the proper environmental and soil-protection measures, regulations, and capacity building activities. Farmers in rural Kazakhstan's areas should be well-informed about the quality of the water resources they use. Water reserves areas, which are used for the people's water consumption household needs, should be protected properly. Such water grouping and soil-water analysis efforts will help preserve and use the farming lands more efficiently. Maintaining the proper land soil-water classifications will help to optimize financial expenses on water purification programs and prevent using potable household water for irrigation purposes. Sustainable development of agricultural production requires proper water monitoring, especially during and after floods. Floods bring an increased level of dangerous pollutants and require substantial investment and investigation programs on a permanent basis. Kazakhstan has experienced droughts during several years and major floods in 2024, which requires developing proper water management strategies, including the efficient water and soil pollution monitoring system. In 2023, Kazakhstan created the Ministry of Water Resources and Irrigation (MWRI), which will receive substantial financing to support programs related to water issues. The aim of our study is to provide the preliminary investigations of West Kazakhstan's (WK) water resources issues and to bring attention to WK soil problems. MWRI could provide more support in the proper water and soil monitoring programs. Already basic activities have been carried out, from monitoring to chemical studies of groundwater and soils with subsequent categorization for further continued more detailed and permanent soil and water monitoring programs. The current investigation efforts are a small part of our promotional efforts to encourage expansion of proper water and soil quality investigations in WK.

Materials and methods

Research area

The WK region is located on the Pre-Caspian plain in CA. The WK region is a transition zone between Russia's Volga-Ural area in Western Siberia lands and Kazakhstan's prairies and steppes^{32,33}. The east part of the WK region is Kazakhstan's Torgai and Aral table-land Plato. The WK region is mostly flat, prairie, steppes landscape, with small highlands, and low elevation mountains in the south. The south part of WK has the transitional Mugodzhgar Range that leads to the mountainous Mangystau region^{34,35}. The WK region is located on the transboundary Russian-Kazakhstan Ural River basin that is connected to the Caspian Lake and consists of the smaller sub basins. These sub basins are the Zhaiyk, Ileik, Uil, Zhem, Sagiz. WK's groundwater resources aquifer systems are located on the Pre-Paleozoic and Paleozoic rocks crop, especially in the Zhaiyk-Mugojar area^{36,37} (Fig. 1).

Geological description of the WK research area

The formation, distribution, depth, qualitative composition, and quantity of groundwater resources in the WK territory are impacted by surface relief, climate factors, surface runoff, geological structure, and soil and vegetation cover. WK's hydrographic network is a part of the transboundary Russian-Kazakhstan Ural-Caspian basin. The hydrographic network was formed in pre-Quaternary and ancient Quaternary times (Fig. 2). Depending on the physical and geographical conditions, the catchment areas' soil salinity, mineralization and chemical compositions can be unstable with sharp seasonal fluctuations^{38,39}. The soil and vegetation cover are diverse, influenced by the land's relief, frequent changes in the lithological and mechanical composition of the soil-forming rocks, as well as variations in moisture levels and salinity. Natural climatic zones are divided into steppe (prairie) zones, semi-desert zones and desert zones. The steppe (prairie) zone is characterized by dark chestnut soils with areas of chernozem and mixed grass-cereal vegetation (loams, clay soil, sandy loam soil, salt marshes). The semi-desert and desert zone is covered by light chestnut or gray-brown soils (salt licks,

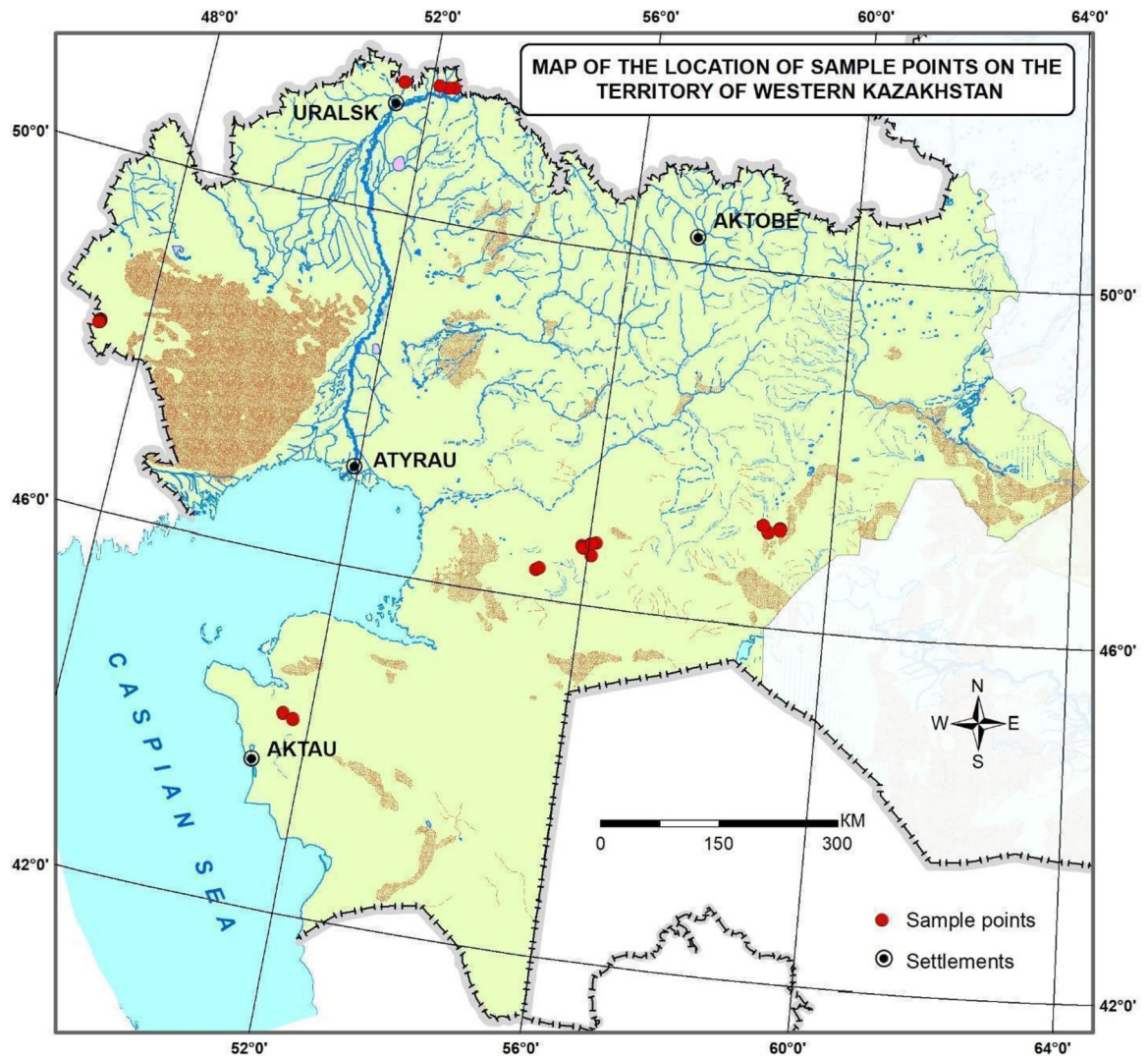


Fig. 1. The West Kazakhstan region, located within the Ural-Caspian Basin, with water sample collection points marked in red. The map was created by Adenova using ArcGIS 10.8.2.

solonchaks, sandy loams, sandstones). The territory of the Caspian lowland soil is mainly highly saline, it is associated with the spread of solonetz, solonchaks. Groundwater has a complex chemical composition and variegated mineralization. The WK region is widely populated with groundwater from marine, lacustrine-marine and alluvial-marine deposits associated with various stages of Caspian transgressions. The deposits are predominantly clayey. The geological age of WK rocks is considered from Precambrian rocks (quartzites, shales, amphibolite); Devonian deposits (conglomerates, sandstones, tuffs, porphyrites, sandstones); Carboniferous deposits (mudstones, dolomites, siltstones); Permian deposits (mudstones, conglomerates, limestones, clays); Triassic deposits (siltstones, mudstones, clays, limestones and marls); Jurassic deposits (sands, sandstones, limestones, marls, sandstones); Cretaceous deposits (sands, limestones, clays, siltstones, sandstones); Neogene deposits (sandstones, clays, sands, conglomerates, marls, loams); to Quaternary deposits (clays, sands, quartz, pebbles, loams, sandy loams)^{38,39}.

Soil and water samples chemical analysis

Soil and water samples were collected in 2023 (Fig. 2). These samples were analyzed for anions, cations, hydrogen pH concentration, TDS, total water hardness C, sodium adsorption ratio (SAR), and sodium content (SC). From the processed field data, Piper and Durov Diagrams were prepared. The V.A. Sulin classification method divided the processed soil water samples into three group areas: (1) potable household; (2) technical irrigation; and (3) unsuitable for use.

Preparatory work for field sampling involved collecting and analyzing prior studies, including local reports, publications, and archive documents. An overview map of the territory was created. This map shows research areas and sampling points. A catalog of hydrogeological wells and springs, including geographic coordinates, was also prepared. A point sampling strategy was employed due to the non-uniform water flow and variability in the measured indicators, as well as the potential for contamination. Sterilized glass bottles were prepared by pre-

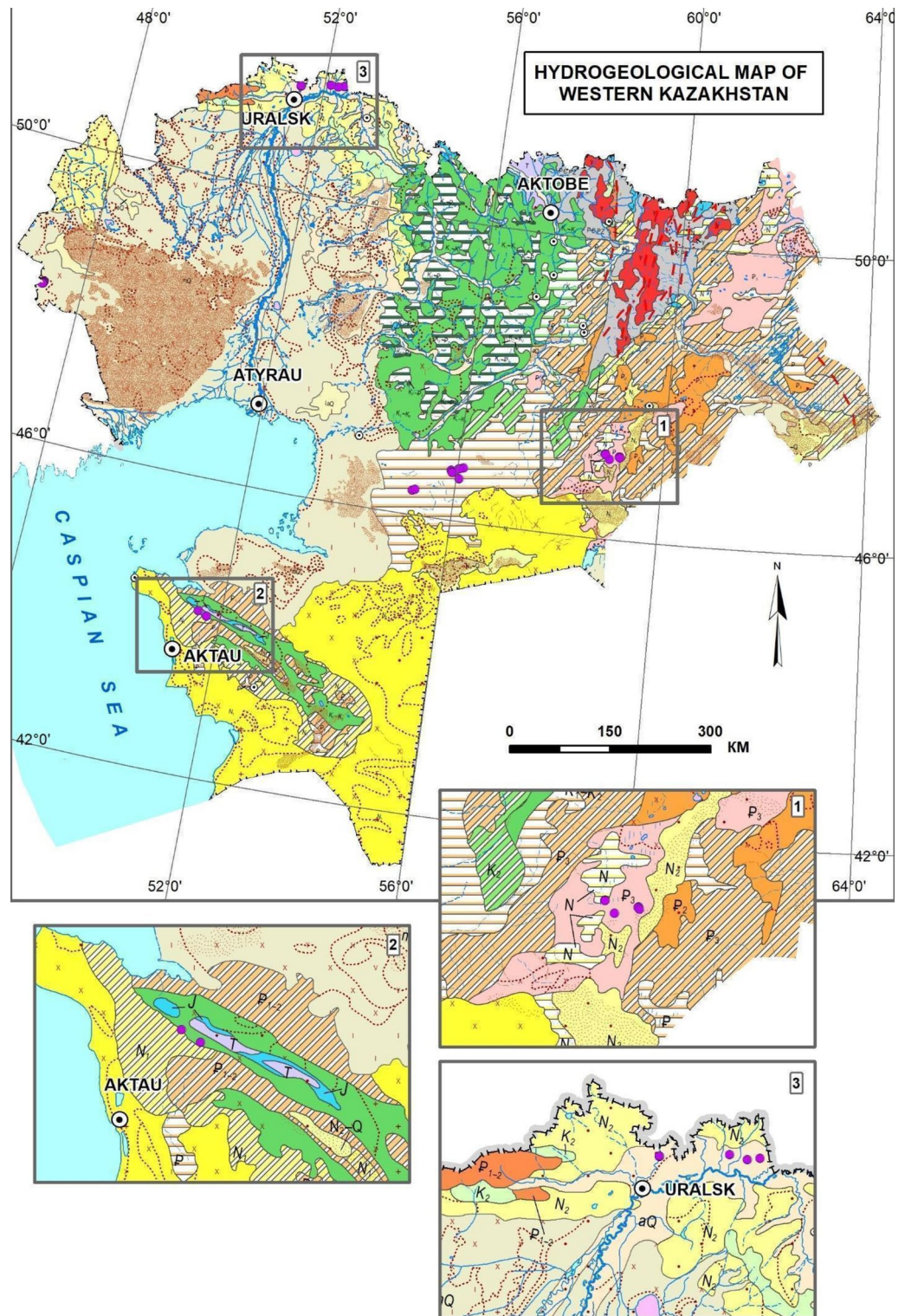


Fig. 2. Hydrogeological map of Western Kazakhstan with sample points. The map was originally prepared by co-author Smolyar [30] and was updated, digitized, modified by co-author Adenova using ArcGIS 10.8.2.

cleaning with diluted nitric acid. To collect samples, bottles were secured with a stopper attached to a cord and placed into a heavy frame. The bottle was lowered to the desired depth, measured by a barometer. The stopper was removed using the cord, allowing the bottle to be filled. Expeditionary research, including the sampling of groundwater and soils, was conducted to assess the current state of groundwater resources.

In the WK research area 27 water samples were collected, as well as 36 soil samples. Soil samples were collected in 36 locations within the limits of groundwater sample collection areas by the “envelope” method.

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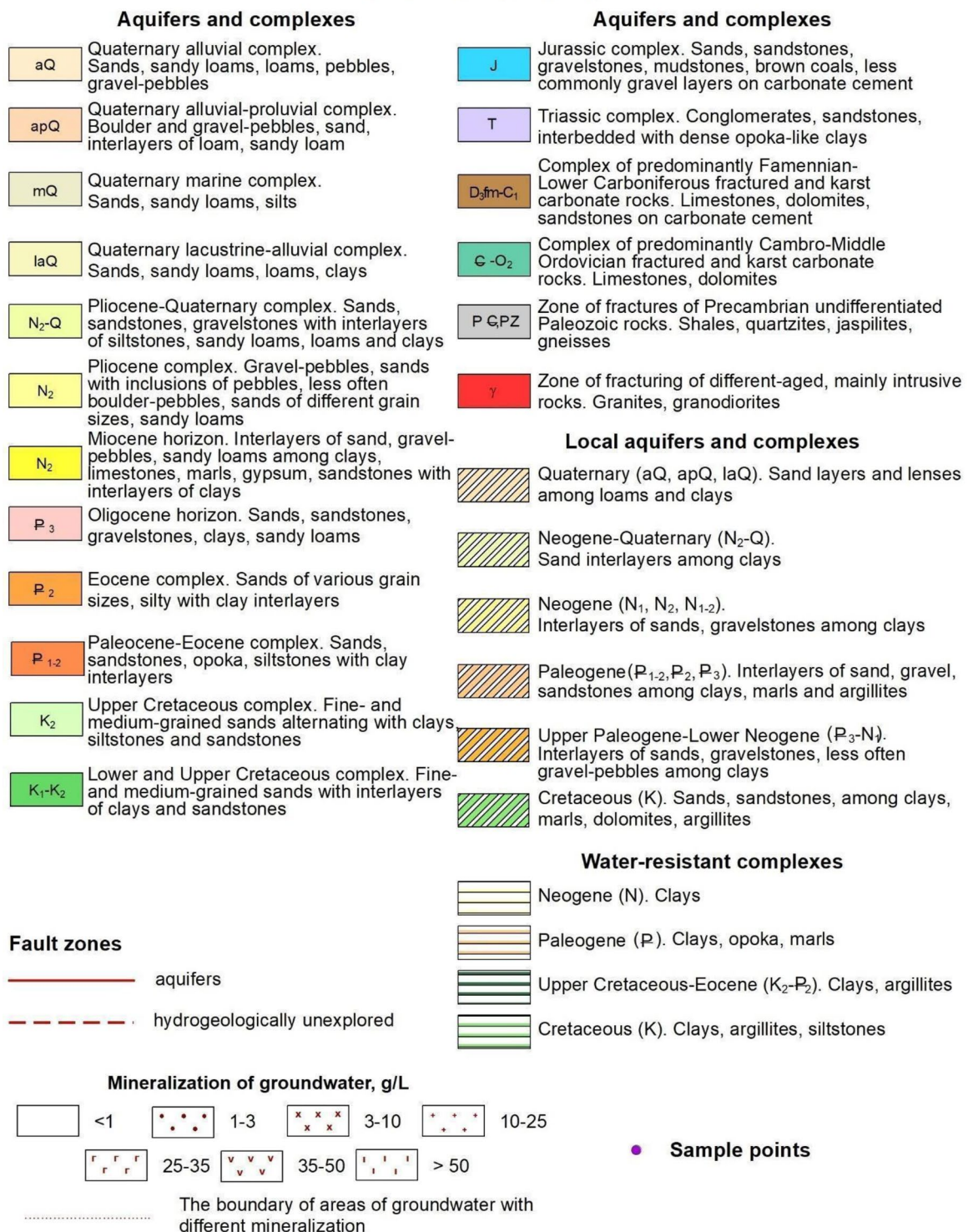


Figure 2. (continued)

The five-point soil samples were taken on site with square dimensions of 5 × 5 m. Four samples formed the site corners, with one sample taken from the center, forming an “envelope.” The soil samples were collected from the depth of 0.2 m and 0.5 m. Various tests were performed on soil and subsoil samples. This includes soil particle size analyses, water-salt extract test, and determination of humus and oil products content. These laboratory test methods and equipment are summarized in Table 1.

The field water samples were collected from 27 wells with GPS Garmin eTrex 10 devices location tracking. The preliminary hydro chemical tests analyses were provided in the field. Water samples were collected in sterile

Parameters	Methods	Inaccuracy	Equipment	Regulatory document
Hydrogen index	Electrometric	0.1 pH unit	Seven Compact, Mettler - Toledo fluid analyzer	GOST 26423-85
Dissolved solids	Gravimetric	5%	OHAUS laboratory electronic scales	GOST 26426-85
Sulphates	Gravimetric		Burette, 100 m	GOST 26428-85
Calcium	Titrimetric			ST RK 1286–2004
Magnesium				GOST 26425-85
Hydro carbonates				
Chlorides				
Sodium	flame-photometric	7.5%	PFP flame photometer, 7 Jenway Limited	GOST 26427-85
Potassium		10%		
Nitrates	Photometric	20%	Shimadzu Corporation UV spectrophotometer	GOST 26488-85
Humus				GOST 26213-91
Fluorides	electrometric	11%	Seven Compact, Mettler - Toledo fluid analyzer	ERD F 16.1:2.2.3:2.2.69-10
Oil products	Fluorometric	17%	Fluorat fluid analyzer LUMEX marketing LLC	Measurement Procedures 03-03-2012
Grain-size composition	Sieve	1%	Testing sieve, OHAUS laboratory electronic scales	ST RK 1273–2004

Table 1. Methodology, methods, and equipment for performing soil and subsoil samples laboratory tests^{40–43}.

Component	Testing methods	Component	Testing methods
Sodium	GOST 26449.1–85	Iodides	GOST 23268.16-78
Potassium		Bromides	
Calcium		Ammonium	GOST 33,045 – 2014
Magnesium		Iron (+ 2)	ST RK ISO 6332 – 2008
Carbonates		Iron (+ 3)	
Hydrocarbonates		Li, Sr, Rb, Cs	ST RK ISO 17294-2-2006
Chlorides		Sulphates	ST RK 1015-2000
Total water hardness		Fluorides	ST RK 2727 – 2015
SiO ₂		Nitrates	GOST 33,045 – 2014
Dry residue		Nitrites	
pH	CT PK ISO 10,523 – 2013	Boron	Environmental Regulatory Documents Federative 14.1:2.4.36-95

Table 2. Methods for conducting laboratory tests of water samples^{44–50}.

150 ml plastic bottles. The bottles were rinsed three times with sample water. The bottles were then filled within four cm from the top and immediately closed to avoid air impact. Each bottle was then labeled for identification. The bottle samples were then placed into a cooler with ice for laboratory delivery within one day. These 27 groundwater samples were analyzed in the Ahmadsafin Institute of Hydrogeology and Geo ecology laboratory for hydrogen ions pH concentration, TDS, total water hardness C, sulfate (SO_4^{2-}), chloride (Cl^-), bicarbonate (HCO_3^-), magnesium (Mg^{2+}), calcium (Ca^{2+}), potassium (K^+) and sodium (Na^+). The anions and cations concentration were analyzed first in the laboratory. Next, calcium, magnesium and hydro carbonates were tested with titration method⁴⁰. Nitrates, nitrides, sulfates, and chlorides were determined by capillary electrophoresis method. Sodium and iron were analyzed by inductively coupled plasma spectrometry. Cations (Ca^{2+}), (Mg^{2+}), (Na^+) and (K^+) and anions (HCO_3^-), (SO_4^{2-}) and (Cl^-) analysis methods are presented in Table 2.

Results of the chemical analysis in the laboratory showing concentrations of different cations (Ca^{2+}), (Mg^{2+}), (Na^+) and (K^+) and different anions (HCO_3^-), (SO_4^{2-}) and (Cl^-) from 27 samples are presented in Table 3. Table 3 presents the results TDS, C, SAR, SC.

The Aqua Chem 13 software, <https://www.waterloohydrogeologic.com/products/aquachem/>, developed by the Canadian Waterloo Hydrogeologic, group was used to present the chemical output of the 27 water samples the Piper and Durov graphic diagrams, which represented major anion-cation water compositions, and V.A. Sulin classification, which reflects the key macro-components content, along with the salinity ratio and pH values. Below is Fig. 3, a map with coordinates for collecting water and soil samples in the study area.

Results output discussion

The concentration of ions in different sampling sites varies. This is due to the geological and natural diversity of the WK territory. The WK study area is divided into several natural and climatic zones. Each zone has peculiar characteristics defined by their geographical location and climate. This leads to hydrogeochemical zoning.

Water sample	Na ⁺ , mg/L	K ⁺ , mg/L	Ca ²⁺ , mg/L	Mg ²⁺ , mg/L	HCO ₃ ⁻ , mg/L	Cl ⁻ , mg/L	SO ₄ ²⁻ , mg/L	pH	TDS, mg/L	C, mg/L	SAR, mEq/L	SC, %
1	649.0	8.6	57.1	35.2	170.8	585.0	574.1	7.8	2089.8	287.0	45.1	83.1
2	543.9	3.2	12.0	1.8	277.6	304.9	465.1	8.3	1616.3	37.3	11.8	96.9
3	682.5	7.1	42.1	15.8	189.2	645.3	674.6	7.9	2265	169.9	38.4	89.7
4	695.4	6.5	24.0	9.7	238.0	611.6	609.2	8.1	2202	99.7	30.2	93.8
5	634.8	5.9	18.0	7.3	213.6	452.1	535.1	8.0	1874	74.9	23.9	94.8
6	708.4	8.1	61.1	46.8	177.0	698.5	699.7	7.9	2408	344.5	57.2	81.8
7	43.5	23.5	74.1	40.7	500.4	72.0	49.8	7.5	827	352.0	3.5	26.0
8	10.0	21.7	33.1	21.3	305.1	13.1	2.1	7.2	423	170.0	0.5	22.5
9	20.1	5.0	23.0	12.8	207.5	10.3	2.1	7.2	294	109.9	0.9	31.3
10	404.0	12.6	8.0	29.2	500.4	531.9	2.1	7.3	1515	139.7	20.7	86.4
11	617.5	7.0	145.2	65.6	234.9	755.2	522.7	7.3	2354.8	631.9	67.5	68.1
12	678.1	5.8	139.3	65.1	219.7	967.6	436.3	7.4	2518	615.1	73.1	70.6
13	1439	16.9	521	255.4	109.8	2326	1955	7.1	6630	2349.6	303.4	57.2
14	401.9	2.0	31.1	14.0	289.8	265.9	391.0	7.9	1402	135.1	20.3	86.6
15	1651	9.2	23.04	11.5	475.9	1684	580.3	7.9	4444.3	104.6	73.6	97.1
16	1484.5	8.2	19.0	7.3	479.0	1687	621.5	8.0	4316	77.4	56.8	97.6
17	28.0	2.9	8.0	17.6	158.6	24.8	14.8	7.8	259	92.1	1.2	41.1
18	43.5	1.15	5.01	2.0	158.6	24.8	14.8	8.4	281.4	20.7	2.3	39.4
19	46.7	1.2	15.0	18.2	198.3	17.7	10.3	8.2	306	112.1	2.1	47.8
20	186.5	2.7	125.3	48.0	378.3	74.5	410	7.4	1232	365.3	18.3	44.5
21	267.5	3.8	54.1	30.4	372.2	237.6	127.6	7.6	1102	259.8	18.8	69.2
22	578.0	0.0	130.0	74.0	372.0	850.0	371.0	7.0	2389	628.4	63.0	66.6
23	298.0	0.0	34.0	18.0	409.0	247.0	125.0	7.8	1150	158.8	16.3	80.3
24	332.0	0.0	54.0	23.0	457.0	168.0	325.0	7.7	1368	229.3	21.8	75.8
25	126.0	0.0	52.0	23.0	403.0	63.0	74.0	7.4	754.0	224.3	8.2	54.9
26	266.0	0.0	82.0	21.0	397.0	220.0	222.0	7.8	1218	291.1	74.8	12.1
27	215.0	0.0	40.0	16.0	372.0	116.0	160.0	7.8	938.0	165.6	12.0	73.8

Table 3. Concentrations of different anions, cations, and different indicators from the 27 water samples.

The chemical composition of groundwater reflects the interactions of all landscape geological components. The leading factor determining the zonality of natural conditions is the climate, the derivative of which is soil zonality. The relationship between hydrogeochemical zoning and soil zoning is especially pronounced in small-scale hydrogeochemical mapping. The background of regional regularities in the chemical composition of groundwater formation related to the certain deviations due to structural, tectonic, geomorphological and hydrogeological conditions, features of the petrochemical composition and metallogenic rocks differences.

The “Sanitary and Epidemiological Requirements for Water Sources, Places of Water Intake for Domestic and Drinking Purposes, Domestic and Drinking Water Supply and Places of Cultural and Domestic Water Use and Safety of Water Bodies”, which was approved by the Order of the Minister of National Economy of the Republic of Kazakhstan dated 16 March 2015 No 209 [Order of the Ministry of National Economy of the Republic of Kazakhstan on Sanitary Rules, 2015] is used for water quality classifications. The list of standardized indicators of the Sanitary Rules, in addition to the usual macro components of the chemical composition of groundwater (Cl⁻, SO₄²⁻), contains many micro components (F, Fe, Mn, As, Be, Sr, Mo, Se, Zn, Cu, Pb, Cd, Cr, Hg), among which two groups are distinguished, differing in concentration and biochemical significance.

Groundwater chemistry

Concentrations of different anions and cations from the 27 water samples (Figs. 4 and 5) include bicarbonate (HCO₃⁻), chloride (Cl⁻), sulfate (SO₄²⁻), calcium (Ca²⁺), magnesium (Mg²⁺), sodium (Na⁺) and potassium (K⁺). Anion's concentration level for bicarbonate varies from 109.8 mg/L to 500.4 mg/L; chloride varies from 10.3 mg/L to 2326 mg/L; sulfate from 2.1 mg/L to 1955 mg/L (Fig. 4). Cation's concentrations level for calcium varies from 5.01 mg/L to 145.2 mg/L; magnesium varies from 1.8 mg/L to 255.4 mg/L; sodium concentration varies from 10.0 mg/L to 1651 mg/L; potassium varies from 0.0 mg/L to 23.5 mg/L (Fig. 5).

The highest anions and cations concentrations were found in water samples # 13 and # 15, while the lowest anions and cations concentrations were found in water sample # 17 (Figs. 4 and 5). Hydrogen ion concentration pH, total dissolved salts TDS, and total water hardness C were also determined in all 27 water samples (Table 3). Hydrogen ion concentration pH is solution acidity or alkalinity index. The pH level varies from 7.0 to 8.4, which is neutral and weakly alkaline. Total dissolved salts TDS identifies the nature of groundwater quality and degree of its pollution^{51–53}. The TDS level varies from 259 mg/L to 6630 mg/L (Table 3). The highest values of TDS were recorded in the north-eastern and eastern parts, and the lowest – in the south-eastern part (Fig. 2). Total water hardness C is expressed in terms of calcium carbonate equivalent⁵⁴:

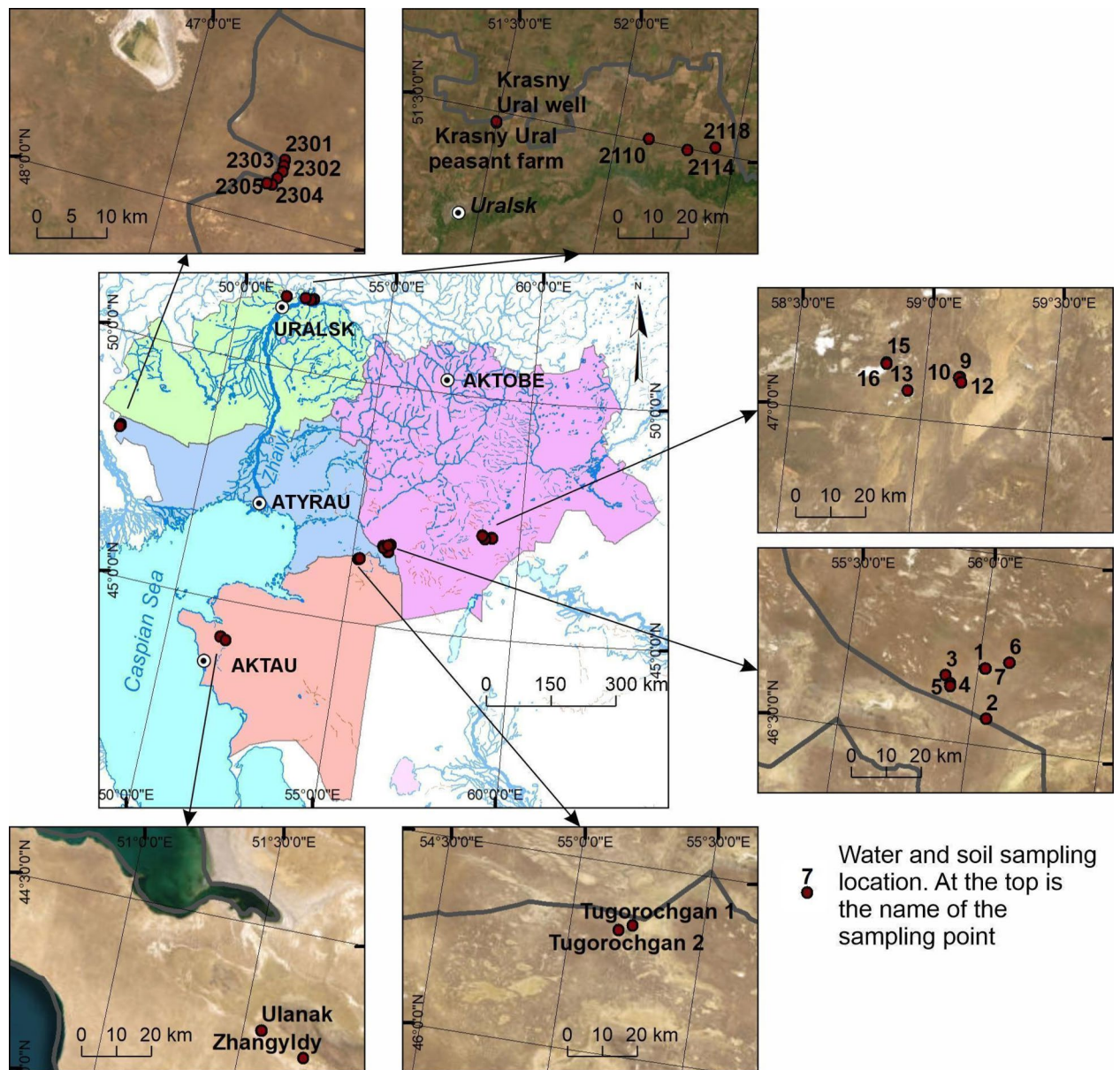


Fig. 3. Water and soil sampling location in the WK region, the map was prepared by author Adenova using ArcGIS 10.8.2.

$$C = 2.5 (Ca^{2+}) + 4.1 (Mg^{2+})$$

where C, (Ca^{2+}), (Mg^{2+}) in mg/L.

Total water hardness C depends on the presence of alkaline-earth elements, calcium, and magnesium⁵⁵. The hardness C level varies from 20.7 mg/L up to 2349.6 mg/L (Table 3). The lowest values of hardness C has shown in the sample # 18 from the north-eastern part, and the highest hardness C has shown in the sample # 13 from the western part of the region (Figs. 1 and 2).

Classification of hydro chemical facies in the WK region

The interaction between soil – rock – reservoir

Throughout the WK territory the main source of replenishment of fresh and slightly brackish groundwater resources is atmospheric precipitation and, to a lesser extent, river water. Fresh and slightly brackish underground waters of WK territory are most susceptible to the influence of climatic factors and are characterized by a weak degree of protection from natural pollution.

In WK territories, the formation of fresh groundwater resources occurs mainly due to the infiltration of atmospheric precipitation, in areas of the outcrop or shallow occurrence of water-bearing rocks of various ages

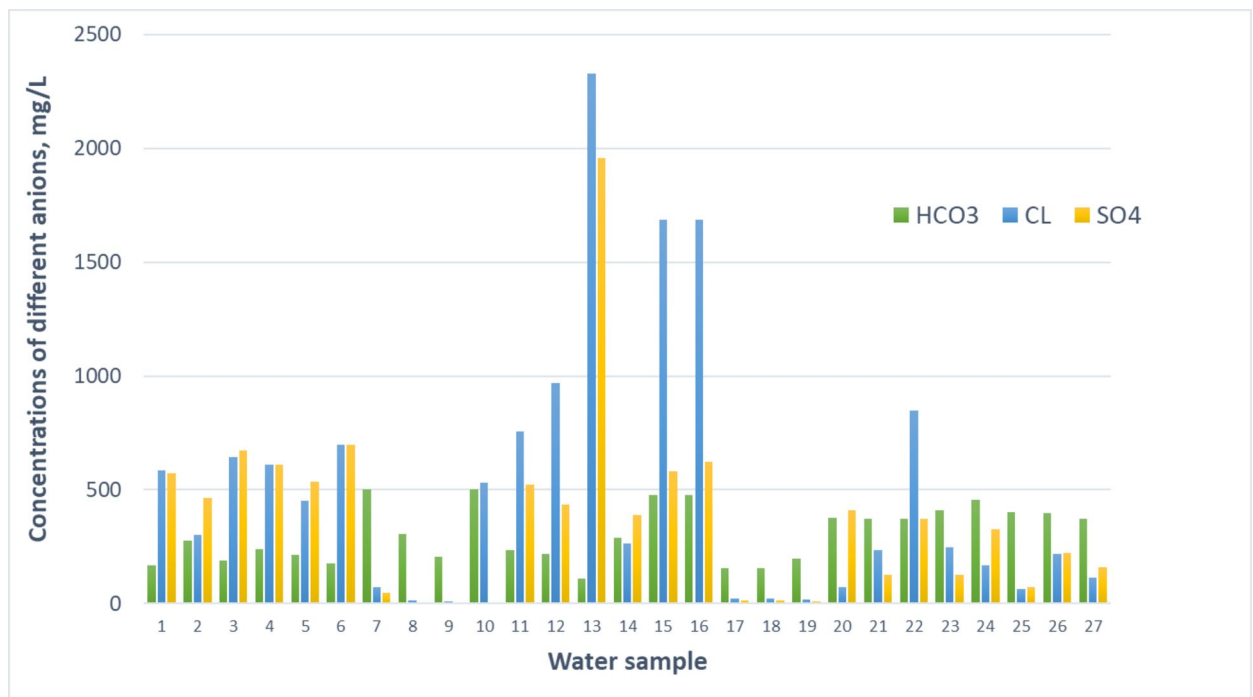


Fig. 4. Concentrations of different anions (HCO_3^-), (Cl^-) and (SO_4^{2-}) in the WK region.

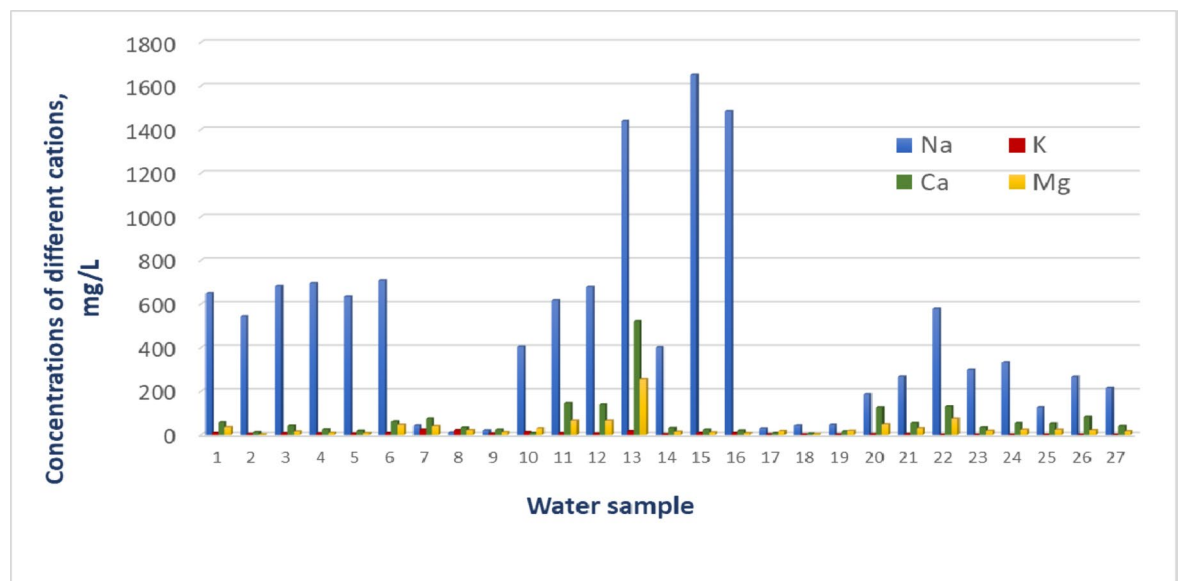


Fig. 5. Concentrations of different cations (Na^+), (K^+), (Ca^{2+}), and (Mg^{2+}) in the WK region.

and genesis, and the filtration of river waters in river valleys. This includes rocks of the Quaternary, Neogene and Paleogene ages, as well as more ancient ones (Fig. 2).

The geological plate of the Caspian Depression within the WK territory and adjacent structures is characterized by numerous tectonic faults and salt-dome tectonics. These features, along with continuous changes in geomorphological and climatic conditions, create diverse conditions for the recharge, movement, and discharge of groundwater. Fresh water is common near the feeding area (northern and northeastern outskirts of the Caspian Depression), where water-bearing rocks come to the surface or lie under a cover of permeable rocks. As the aquifers subside in the central part of the Caspian Depression, an increase in the mineralization of groundwater to brines is observed. Here, the pressure allows wells to spontaneously flow. Near the water recharging area (Mount Mugolzhari), the underground waters of the Albian-Cenomanian are characterized by low mineralization and are used for domestic and drinking water supply of large settlements, oil fields and small

farms. As the distance from the feeding area increases and the water-bearing rocks sink to greater depths, the mineralization of the underground waters gradually increases, reaching brines in the central part of the Caspian depression (Fig. 2).

A special place in the provision of underground waters to the population of cities, settlements and mining enterprises is occupied by underground waters of quaternary alluvial deposits of river valleys. On the basin's territory, aquifers made up of alluvial deposits are the main source of water supply for the region's population. As a rule, river valleys are filled with loose clastic deposits with a thickness of 5–8 to 25–30 m with high water yield. Depending on the thickness of the alluvium and its filtration properties, the productivity of production wells can reach several tens of liters per second, and water intakes several hundred.

For the classification of the 27 groundwater samples the V.A. Sulin⁵⁶ method was applied. This Sulin method divides water into four types: (a) sodium-sulfate; (b) sodium-bicarbonate; (c) magnesium chloride; (d) calcium-chloride. The ratio of individual ions quantities (in milligram-equivalents) established by laboratory analysis makes it possible to determine water type for hydro chemical facies (Table 3). Durov (Fig. 6) and Piper (Fig. 7) diagrams were applied for displaying water basic chemical components.

V.A. Sulin water classification

The V.A. Sulin groundwater classification is based on a genetic principle. This genetic principle states that water chemistry results from specific natural conditions (continental, marine, or subsurface) and through the interaction of water with rocks or with water of different origins. There are many water classifications based on their chemical composition, such as S.A. Shchukarev, N.I. Tolstikhin, and V.A. Sulin classifications. The S.A. Shchukarev classification is based on the one or more of the three main anions (Cl^- , SO_4^{2-} , HCO_3^-), making up more than 12.5% of the composition, and one or more of the three cations (Na^+ , Ca^{2+} , Mg^{2+}) making up more than 12.5% of the composition. The N. I. Tolstikhin classification method is based on the water classification in three classes by the predominant anion: hydrocarbonate, sulfate, and chloride. Within the classes, three subclasses are distinguished (by the predominant cation): calcium, magnesium and sodium.

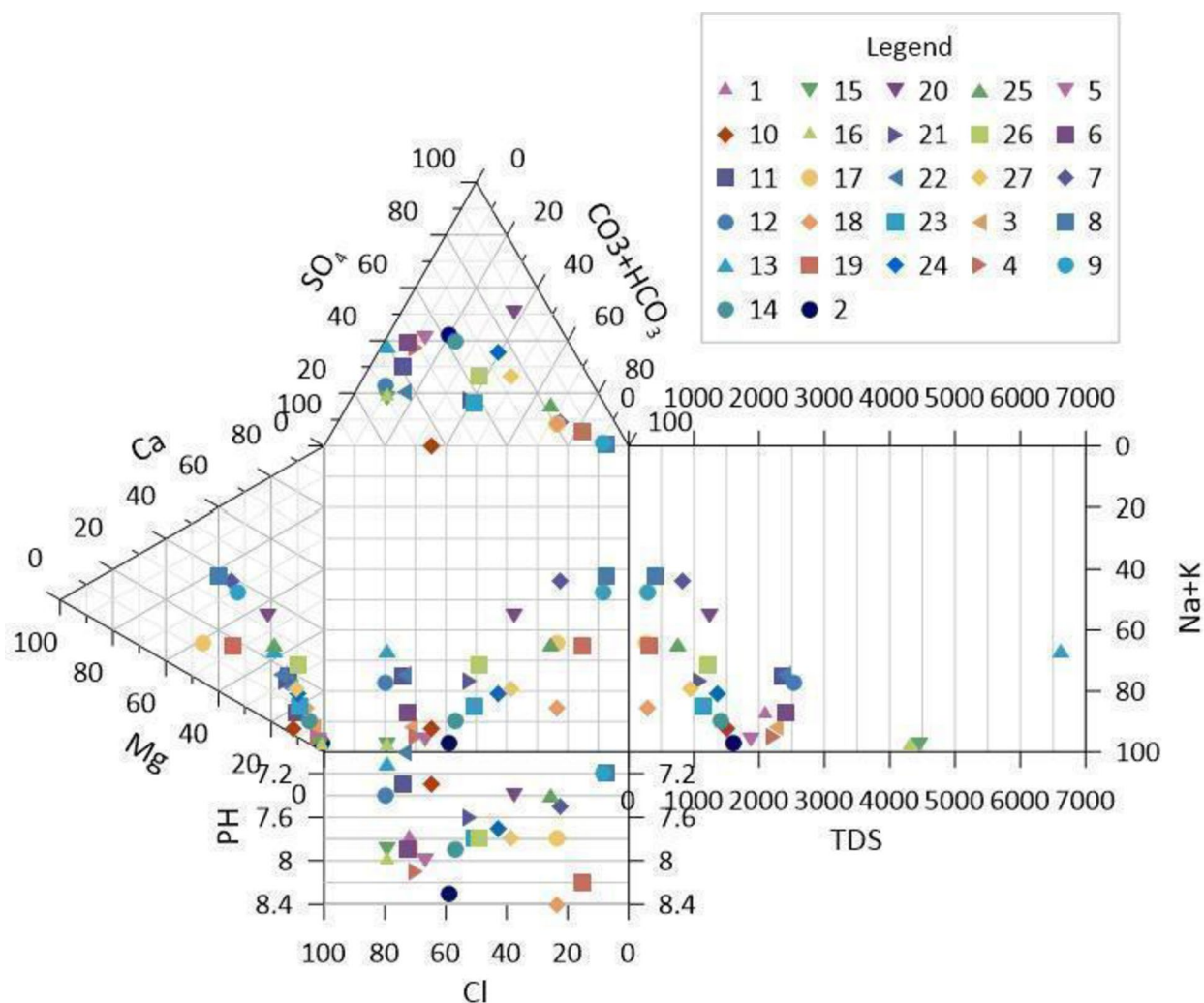


Fig. 6. The Durov Diagram represents the major water compositions in the WK region.

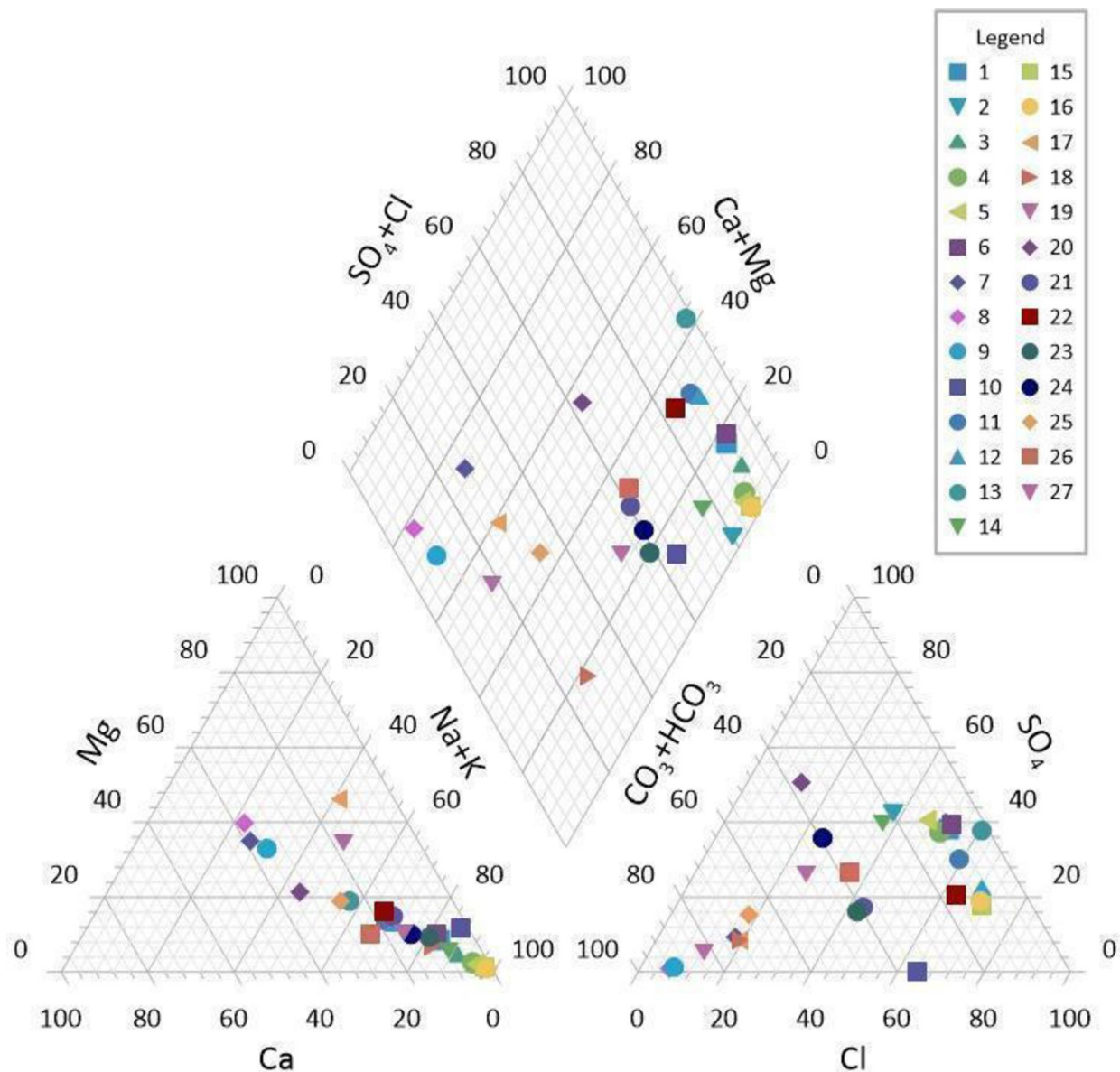


Fig. 7. Piper Diagram represents major water compositions.

Diagnostic factors water type (mg*E)	Water type	Water formation characteristic circumstances	Ions	Mean	Median
$\frac{Na}{Cl} > 1$	$\frac{Na-Cl}{SO_4} \ll 1$ Sodium-sulfate (Na ₂ SO ₄)	Water of ground surface and unobstructed water exchange (continental)	Cl ⁻	505.7	265.9
	$\frac{Na-Cl}{SO_4} > 1$ Sodium-bicarbonate (NaHCO ₃)	Water of ground surface and unobstructed and obstructed water exchange (continental)	Na ⁺	483.3	401.9
			HCO ₃ ⁻	305.8	289
$\frac{Na}{Cl} \ll 1$	$\frac{Cl-Na}{Mg} \ll 1$ Magnesium chloride (MgCl ₂)	Sea and ocean water and water of obstructed water exchange (marine)	Ca ²⁺	67.7	40
	$\frac{Cl-Na}{Mg} > 1$ Calcium-chloride (CaCl ₂)	Water of absent or obstructed water exchange especially with its high salinity (subsurface)	SO ₄ ²⁻	369.1	371

Table 4. Determination of water type by V.A. Sulin classification.

The classification of V. A. Sulin method is used in Kazakhstan, especially among natural resources exploration companies, such as oil specialists. Water is classified by the characteristic ratios of the main ions, known as genetic coefficients. Using these coefficients, four genetic types of water are identified: $rNa+/rCl^-$; $r(Na+-Cl^-)/rMg^{2+}$; $r(Cl-Na+)/rSO_4^{2-}$ (Table 4). Sulfate-sodium type waters are typical for zones of open occurrence of

strata. Chlorine-calcium brines are usually found in deep horizons, in conditions of stagnation or difficult water exchange. Hydro carbonate-sodium waters of low mineralization are known in areas of open occurrence of rocks with high mineralization and increased chloride content in deep horizons with difficult water exchange. More advanced water classification methodologies are applied in the original research articles^{57–59}, which require further studies for assessing hydrogeochemical processes in groundwater.

The type of sodium chloride and chloride sulfate water type prevail the 27 water samples by V.A. Sulin water classification method.

Durov Diagram

A Durov Diagram is used to illustrate compositions of major ions. Values of cations and anions are displayed on two separate triangular panels, with the data points projected on the square grid at the base of each triangle. The pH and TDS are also shown on the Durov Diagram (Fig. 6). The Durov Diagram was prepared with several columns. The ion group percentage is shown in each column. The order of columns used is as follows: (Ca^{2+}), (Mg^{2+}), (Na^+), (K^+), (Cl^-), (SO_4^{2-}), (CO_3), (HCO_3^-). The cation group percentage is calculated from the total cations' concentration of calcium, magnesium, sodium, potassium. The anion group percentage ratio is calculated from the total concentration of sulfates, chlorides, carbonates, and hydro carbonate.

The combined chemical water composition appears as:

$$M \ 1.4 - 6.6 \frac{(Cl) \ 37 - 70 \ (SO_4) \ 38 - 40 \ (HCO_3) \ 2 - 23}{(Na + K)57 - 81 \ (Ca)8 - 24 \ (Mg)6 - 19} Ph \ 7.1 - 8.06$$

Here, the chemical composition of well water is slightly saline, brackish with a mineralization level of 1.5–6.5 mg/L, with a general hardness index from weak to high in the range from 2.8 to 12.7 mg/L. The water's composition is sodium chloride and calcium sodium. The content of nitrates in water is less than 0.2 mg/L, nitrites less than 0.001 mg/L, ammonium 0.1–5.9 mg/L, silicon 0.6–4.9 mg/L, total iron 0.6–2.8 mg/L, oil products - up to 0.27 mg/L, heavy metals, mg/L : Pb - up to 0.03; Cu 0.01–0.02 and Zn 0.002–0.01.

Piper Diagram

A Piper Diagram represents the main water components⁶⁰. The Piper Diagram contains two triangular diagrams projected to a rhombus, which represents the chemical composition of the sample. The cations and anions are shown as separate ternary graphs. The vertices of the cation graph are the calcium, magnesium, and sodium cations plus the potassium cations. The vertices of the anion graph are sulfate, chloride, and carbonate anions plus the hydrogen carbonate anions. The left triangle shows the composition of cations, and the right one - anions. The cations and anions are crossed in the rhombus.

Figure 7 presents the mineralization, TDS, and the distribution of various components based on the locations of hydrogeological wells, along with a Piper Diagram. These visualizations illustrate the concentrations of key macro- and micro-components in the groundwater, as determined by the geochemical sampling conducted. The chemical analysis indicates that the groundwater is predominantly characterized by chloride, sodium, sulfates, bicarbonates, calcium, and magnesium respectively.

The Piper Diagram is a valuable tool for visualizing and classifying groundwater chemistry. By providing insights into the relative abundance of major ions, it supports the evaluation of water quality and the identification of hydro chemical processes affecting groundwater systems. The spatial distribution of groundwater types, as illustrated by the Piper diagram, reveals patterns associated with favorable hydrogeological conditions, recharge sources and potential anthropogenic influences on water quality.

The chemical composition of the groundwater, as determined through laboratory analysis, indicates that it is suitable for irrigation purposes.

Interpretation of groundwater quality for drinking, household purposes and irrigation

The mineralization coefficient by TDS of various components by the location of hydrogeological wells is presented in Fig. 8.

Groundwater in WK has variation in the correlation among the various parameters. Mineralization by TDS and HCO_3^- ($R^2=0.5141$) are low, which may indicate a reduced influence of water-rock interaction processes. The level of mineralization by TDS and Cl^- ($R^2=0.9538$), TDS and Na^+ ($R^2=0.9512$) and TDS and SO_4^{2-} ($R^2=0.8875$) are high (Table 5). This case occurs when a significant number of salts or sedimentation and leaching of marine impurities comes from the Caspian Sea and Aral Sea. Also, intensive agricultural activity in the area may be the cause of this anomaly, as it is associated with the weathering of silicate volcanic rocks, releasing both alkali and alkaline earth metals and forming alkali.

Groundwater quality for drinking, household purposes

The groundwater samples chemical parameters (pH, TDS and C) satisfy both Kazakhstan's (Table 6) and the World Health Organization's⁶¹ water quality requirements for groundwater suitability for drinking and household purposes.

Hydrogen ion pH concentration is neutral and weakly alkaline with pH of higher than 7.

The total dissolved salts TDS and TDS mineralization values of the water samples # 7, 8, 9, 17, 18, 19, 25, 27 are less than 1,000 mg/L, which is classified as fresh. Water in samples # 1, 2, 3, 4, 5, 6, 10, 11, 12, 13, 14, 15, 16, 20, 21, 22, 23, 24, 26 is counted as saltish⁶², and the TDS mineralization values are within range of 1,000–10,000 mg/L. The groundwater is suitable for drinking and irrigation purposes when values of its TDS mineralization are less than 600 mg/L, the water samples from wells # 8, 9, 17, 18 and 19 satisfy this requirement (Table 5).

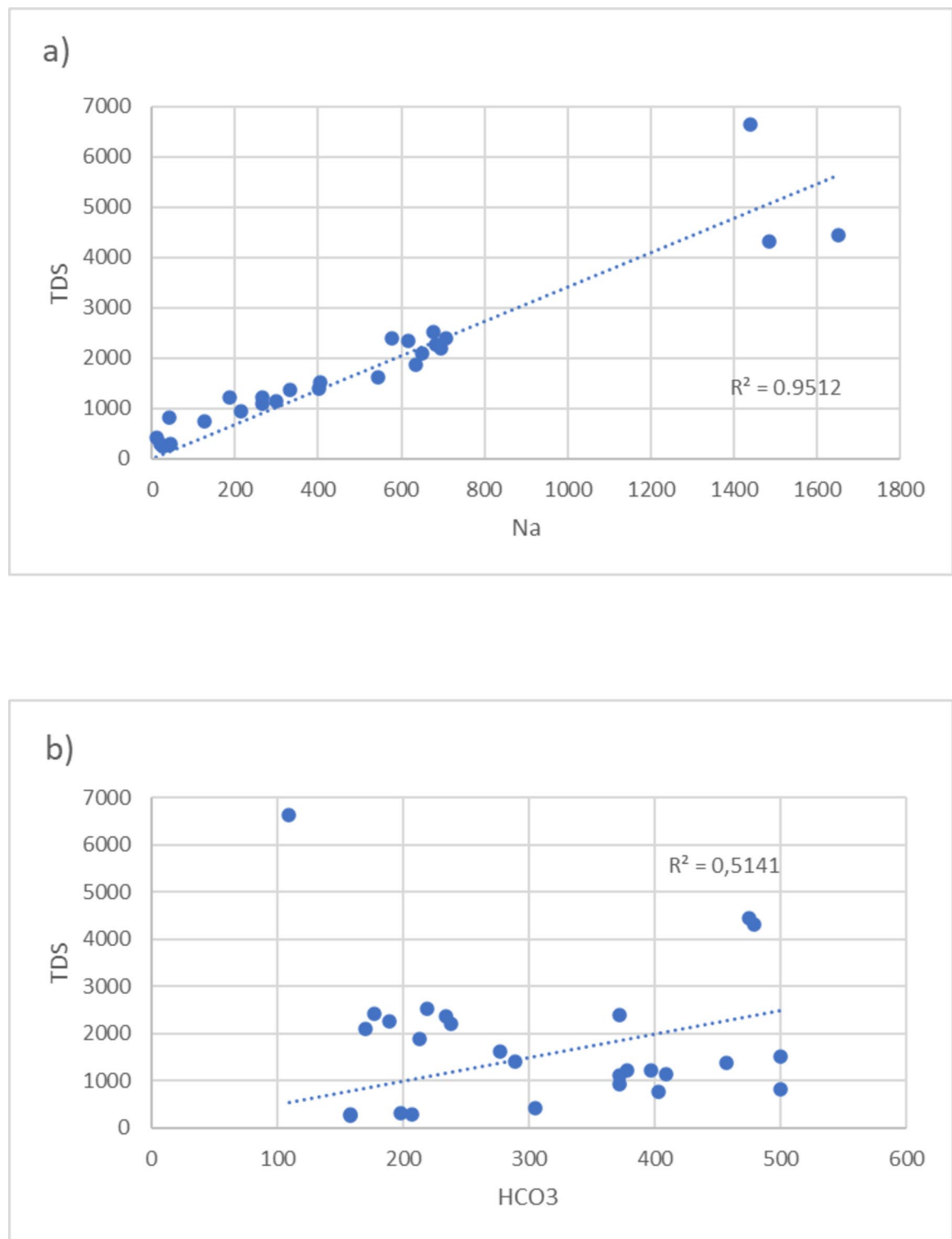


Fig. 8. Correlation between the level of mineralization by TDS and the main ions in well water: (a) TDS-Na; (b) TDS-HCO₃; (c) TDS-Cl; (d) TDS-SO₄.

Water with a total hardness C of 75–150 mg/L is classified as water with medium hardness by Kazakhstan's groundwater quality standards in Kazakhstan for drinking and household use (Table 6). Water in samples # 9, 10, 14, 15, 16, 17 and 19 are within the limits of total hardness C of medium hardness. Water in samples # 1, 3, 8, 21, 23, 24, 25, 26 and 27, with total hardness from 150 to 300 mg/L, are counted as hard. Water in samples # 6, 7, 11, 12, 13, 20, 22, 24, 25 and 26, with total hardness higher than 300 mg/L, is counted hard⁶³. The groundwater is saturated with calcium and magnesium salts.

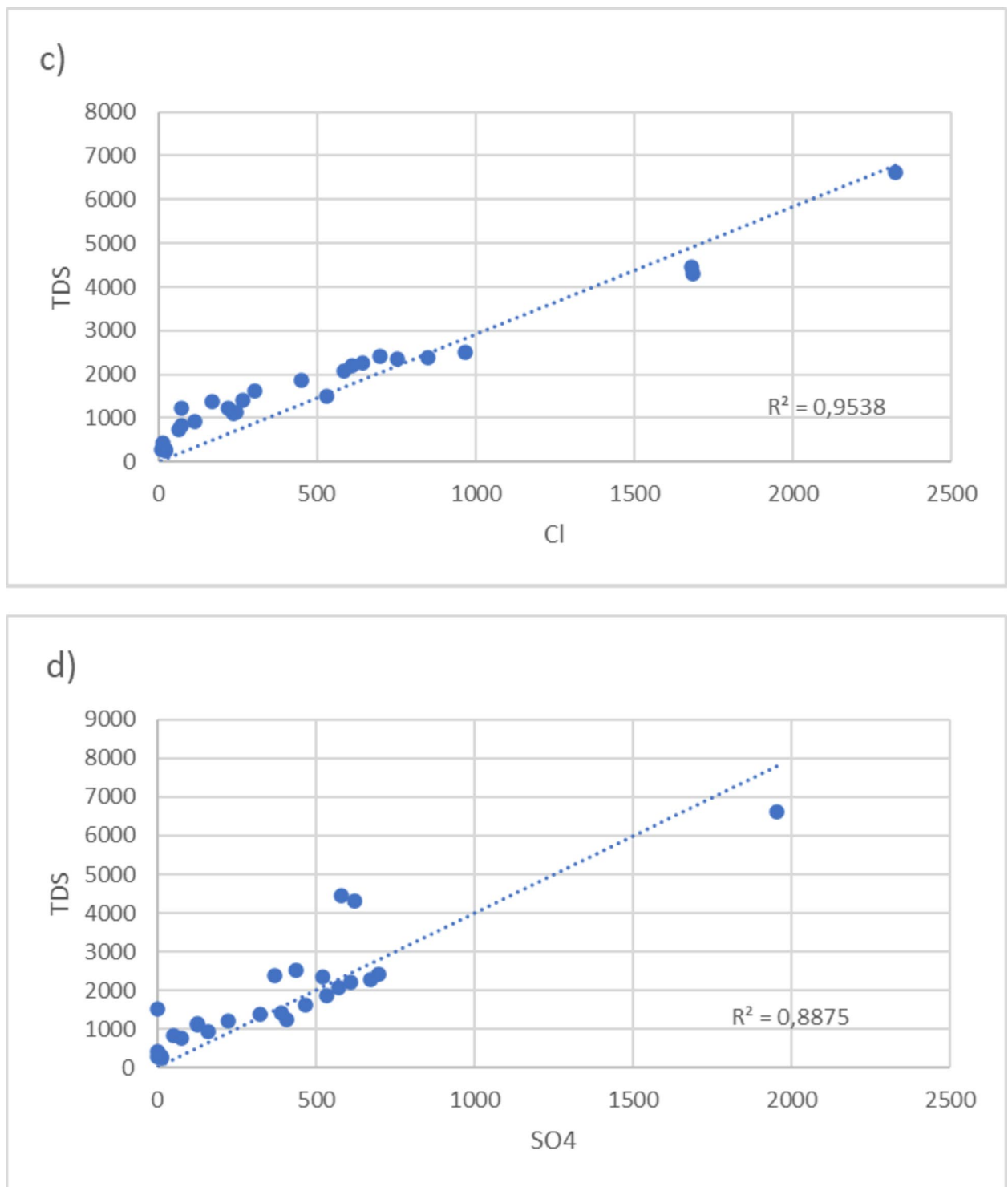


Figure 8. (continued)

The total dissolved salts TDS and total hardness C investigation of the water samples output: (1) water samples # 8, 9, 17, 18 and 19 with total dissolved salts TDS lower than 600 mg/L – is suitable for drinking and irrigation. (2) water samples # 9, 10, 14, 15, 16, 17 and 19 with values of total hardness C ranging within 75–150 mg/L – medium moderately hard water. (3) combined testing analysis of total dissolved salts TDS and total hardness C of water samples # 17, 18 and 19, output that water is suitable for drinking, irrigation and household purposes.

Ions	Unit	Min	Mean	Max	R ²	Interpretation, R ²	
Na ⁺	mg/L	10	401.9	1651	0.9512	1–0.9	Very high correlation
HCO ₃ [−]	mg/L	109.8	289.8	500.4	0.5141	0.89–0.70	High correlation
Cl [−]	mg/L	10.3	265.9	2326	0.9538	0.69–0.50	Moderate correlation
SO ₄ ^{2−}	mg/L	2.1	371	1955	0.8875	0.49–0.30	Low correlation
						0.29–0.00	Little if any correlation

Table 5. Correlation coefficient ranges and interpretation.

Parameter	Water quality classification		Source
Total dissolved salts TDS, mg/L	Fresh	0–1.000	[C. W. Fetter, 2014]
	Subsaline	1.000–10.000	
	Saline	10.000–100.000	
	Increased salinity	> 100.000	
Total water hardness C, mg/L	Soft	0–75	[Z. Sen, 2015]
	Medium hardness	75–150	
	Hard	150–300	
	Very hard	> 300	
Sodium adsorption ratio SAR, mg/L	Excellent	< 10	[D.K. Todd, L.W. Mays, 2005. Z.Sen, 2015]
	Good	10–18	
	Permissible	18–26	
	Dubious	> 26	
Sodium content SC, %	Excellent	< 20	[L. V. Wilcos, 1955]
	Good	20–40	
	Permissible	40–60	
	Dubious	60–80	
	Unsuitable	> 80	

Table 6. Water quality classification standards in Kazakhstan.

Evaluation of groundwater quality for irrigation

The quality of groundwater, especially mineralization and salt composition, influences agricultural crop yields. These two chemical indicators sodium adsorption ratio SAR and sodium content SC were used to analyze the water quality for irrigation purposes.

Sodium adsorption ratio SAR

Suitability of groundwater for irrigation can be determined by the water salinity and sodium adsorption ratio SAR, as sodium concentration will influence both soil permeability and structure⁵⁴. Sodium adsorption ratio SAR was applied:

$$SAR = Na \left(\sqrt{\frac{Ca + Mg}{2}} \right);$$

Concentrations of sodium Na, calcium Ca and magnesium Mg were calculated in milliequivalents per liter (mg/L).

Calculated values of sodium adsorption ratio SAR for all water samples vary from 0.5 to 303.4 mg/L (Table 3). The lowest values of sodium adsorption ratio SAR were recorded in the south-eastern part, wells sample # 8, and the highest values in north-western part, wells sample #13 (Figs. 1 and 2).

The water with a sodium adsorption ratio (SAR) of less than 10 meq/ L is suitable for irrigation purposes^{54,62}. Water in south-eastern and north-eastern parts from water samples # 7, 8, 9, 17, 18 and 19 are suitable for irrigation (Table 7; Figs. 1 and 2).

Sodium content SC

Sodium salt Na clogs soil, it decreases soil permeability, what negatively impacts crops⁶³. Sodium content (SC) %, is determined by the following formula⁶⁴:

$$SC = 100 \frac{Na + K}{(Ca + Mg + Na + K)}.$$

Sodium content (SC) values are varied within limits of 12.1–97.6% (Table 3). The lowest values of sodium content SC were recorded in the central part, or water sample 26, and the highest values were in the north-western part,

Type of salinity chemistry	Ratio of cations mg-eq			Type of salinity chemistry	Ratio of anions mg-eq		
	Ca ²⁺ / Mg ²⁺	Ca ²⁺ / Na ⁺	Na ⁺ / Mg ²⁺		HCO ₃ ⁻ + CO ₃ / SO ₄ ²⁻	HCO ₃ ⁻ + CO ₃ / Cl ⁻	SO ₄ ²⁻ / Cl ⁻
Calcium	γ 4		≤ 1	Chloride	≤ 1		= ≤ 0.25
Magnesium - calcium	1 ≤ ≥ 4		≤ 1	Sulfate - chloride	≤ 1		1-0.25
Magnesium	≤ =0.25	γ = 1		Chloride - sulfate		≤ 1	1-4
Calcium - magnesium	γ 0.25- ≤ 1	γ 1		Sulfate		≤ 1	γ 4
Sodium	≤ 1		γ =4	Soda		γ =4	≤ 1
Sodium - magnesium			1 ≤ = ≤ 4	Sulfate - Soda	1-4		γ 1
Calcium - sodium	γ 1	0.25-1	γ 1	Sodovy	γ 4		γ =1
Sodium - calcium	γ 1	1-4		Soda - sulfate	0.25-1		γ 1
				Soda - chloride		0.25-1	≤ 1
				Sodium - chloride		1-4	≤ 1

Table 7. Types of soil salinization chemistry by cations and anions.

Degree of salinization	Salt content in %		
	Types of salinity chemistry		
	SO ₄ ²⁻ , Cl ⁻ - SO ₄ ²⁻	Cl ⁻ , SO ₄ ²⁻ - Cl ⁻	HCO ₃ ⁻ , Cl ⁻ - HCO ₃ ⁻ , SO ₄ ²⁻ - HCO ₃ ⁻ , HCO ₃ ⁻ - SO ₄ ²⁻ , HCO ₃ ⁻ - Cl ⁻
Unsalted	≤ 0.3	≤ 0.2	≤ 0.1
Weak	0.3–0.6	0.2–0.5	0.1–0.4
Average	0.6–1.0	0.5–0.7	0.4–0.6
Strong	1.0–2.0	0.7–1.0	0.6–0.8
Very strong	γ 2.0	γ 1.0	γ 0.8

Table 8. Assessment of the degree of soil salinization.

or water samples 15 and 16 (Figs. 1 and 2). The groundwater samples are unsuitable from water samples 1, 2, 3, 4, 5, 6, 10, 14, 15, 16 and 23. The sodium content SC value in these wells is higher than 80% (Table 7; Figs. 1 and 2). The groundwater samples are dubious from water samples 11, 12, 21, 22, 24 and 27. The sodium content SC value in these wells is ranging from 60 to 80% (Table 3; Figs. 1 and 2).

Soil quality assessment

The following assessment criteria were applied to evaluate soil quality, or soil salinization levels: the degree and types of soil salinization chemistry, the spatial distribution of saline lands, the causes of salinity, and the salinization level in relation to irrigation suitability. The following categories are: I category) areas with uniform soil cover, soil complexes occupy less than 15% of the area; the area of saline and swampy lands is less than 5%; II category) areas with heterogeneous parent rocks, soil complexes occupy less than 30% of the area; the area of saline and swampy areas is less than 20%; III category) areas with development of more than 30% of areas, floodplains, deltas, rice crop rotations; saline areas occupy more than 20% of the area. The soil salinization levels are distinguished by the ratios presented in the Tables 7 and 8.

Table S1 represents the characteristics and assessment of lands by the degree of salinization (Appendix A). Among the types of salinization chemistry, the most common are chloride-sulfate, soda-sulfate, sulfate-soda by anions, and sodium and sodium-calcium by cations. Soda-saline lands are relatively widespread, the melioration of which requires very large financial and material costs. The content of petroleum products in all soil samples significantly exceeds the maximum permissible concentration.

The aqueous extract of the field soil samples from the WK region were used to rank the degree of soil salinity (Table S2, Appendix B). Soils or individual horizons in which the content of water-soluble salts, the value of dry (dense) residue exceeds 0.30% are considered saline. The following degrees of soil salinity are distinguished: non-saline - salt content less than 0.30%; slightly saline - salt content less than 0.3–0.5%; moderately saline - salt content less than 0.5–1.0%; highly saline - salt content less than 1.0–2.0%; very highly saline - salt content > 2%. The types of soil salinity are established based on the predominance of anions and cations.

Conclusion

Effects of climate change, flood-droughts, and anthropogenic disruptions are widespread in many regions, including CA, Kazakhstan. As a result, it is critical to support and expand proper soil - water resource monitoring, investigation, along with continued evaluations of irrigated farming conditions in Kazakhstan. Climate change issues, along with increasing human disruptions, are important to consider. The existing anthropogenic pressure on land and water resources, including unsustainable engineering and agricultural projects, poses a significant risk of environmental degradation in the Caspian Sea region. This is reminiscent of what happened to the Aral Sea. As a result, permanent and consistent water monitoring and water resources investigation programs are required to expand in Kazakhstan. The proper water monitoring programs require substantial investment and

government legislation support, which is missing in most CA countries. Here, even small-scale water resource investigation programs would be beneficial to implement in the CA regions, including Kazakhstan. Preliminary basic investigations of the WK region with categorization of water resources in three groups by the water-soil quality field investigations were provided. These three categories are: (1) the smallest salinity level, which can be used with minimum purification efforts for the household use; (2) water suitable for irrigation, as water in the technical water quality level, which requires more investment in water purification to be used for the household needs; (3) water unsuitable for irrigation and household use, having the high salt content, which requires substantial water purification investment. Farmers in rural Kazakhstan should be well-informed about the quality of the water resources they use. Water reserves areas, which are used for the people's water consumption and household needs, should be properly protected. These developed water grouping, soil-water analysis efforts will help preserve, use the farming lands more efficiently. The land soil-water classifications will help to optimize financial investments on water purification programs and prevent the use of good quality household water for irrigation purposes. In order to support potable household and irrigation purposes, it is critical to regularly monitor water quality. However, such monitoring can be difficult to provide in many developing countries. Because of this, even periodic independent water sampling would be beneficial for residents in rural areas. Groundwater quality, particularly its mineralization and salt composition, significantly impacts agricultural crop yields.

This case report presents a water assessment conducted in the WK region. Researchers collected a total of 27 water samples and 36 soil samples for chemical laboratory analysis. The research methodology was based on the soil-water samples collection with the laboratory analysis of different anions and cations, concentration of hydrogen ions pH, total mineralization TDS, total water hardness C, and relative sodium adsorption index SAR, sodium content SC. The results of geochemical testing were processed and analyzed with Piper and Durov Diagrams. Water was classified with the V.A. Sulin method. The results show that groundwater in the northeastern part of the WK region is suitable for both irrigation and domestic purposes. Groundwater in the southeastern part of the region is suitable for irrigation, while groundwater in the northwestern part is unsuitable for irrigation, except for crops that can already tolerate very high salinity. The types of soil salinity are classified by the prevalence of anions and cations. The most common salinity chemistry levels are classified as chloride-sulfate, soda-sulfate, and sulfate-soda based on anions, and as sodium and sodium-calcium based on cations. Soda-saline lands were identified in some areas of the WK region. The upgrading of melioration for sufficient water quality improvement will require substantial efforts. The content of petroleum products in some soil samples significantly exceeds the maximum permissible concentration. At the same time, the groundwater in most WK areas is generally environmentally safe, with the groundwater deposits in most areas being proper for household and irrigation use. A further, more detailed investigation is required with more permanent soil water monitoring efforts, especially with the recent flooding events.

Data availability

Data Availability Statement: The groundwater field data presented in this study were collected with Kazakhstan's local authorities' approvals and are available on request from the corresponding author.

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Author contributions

D.A. collected and analyzed the data; M.A., Y.M., D.S., and V.S. supervised the development and further introduction of the work; J.S. analyzed the data, conducted the literature search in English and prepared the final manuscript. All authors have read and agreed to the published version of the manuscript.

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Declarations

Competing interests

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