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Hydrochemical Assessment of Groundwater Quality and Salinization Risk for Drinking and Irrigation Uses in the Arid Yazd-Ardakan Plain, Central Iran

Hamidreza Shahrjerdi
University of Tehran
Aziz Azizpour
University of Tehran
Amirhosein Merrikh
University of Tehran
Arash Kouhi Biladeragh
University of Tehran
Mohsen Mirmohammadi
mirmohammadi.m@ut.ac.ir
University of Tehran

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Abstract

Groundwater quality deterioration and salinization are major environmental concerns in arid and semi-arid regions, where limited surface water resources increase dependence on aquifers for drinking and irrigation. This study provides an integrated hydrochemical assessment of groundwater quality and salinization risk in the Yazd-Ardakan plain, central Iran, as a representative arid aquifer system under severe water stress. A total of 142 groundwater samples collected from 10 monitoring stations between 2002 and 2018 were evaluated using physicochemical parameters, major ions, hydrochemical facies, and irrigation water quality indices, including sodium adsorption ratio (SAR), sodium percentage (Na%), residual sodium carbonate (RSC), and permeability index (PI). The results indicate that groundwater is predominantly characterized by Chloride-Sulfate facies, reflecting strong salinization processes. For drinking purposes, all samples had total dissolved solids above 1000 mg/L, the level above which the World Health Organization describes increasing palatability problems, with concentrations ranging from 1080 to 13,924 mg/L. Elevated chloride, sulfate, and sodium concentrations further indicate poor drinking water quality, particularly at stations W5, W6, W8, W9, and W10. Irrigation suitability assessment showed contrasting results: although 64% of samples had acceptable SAR values and most samples showed favorable RSC and PI conditions, only 17% were classified as excellent to good based on Na%, indicating a significant risk of long-term soil degradation. These findings highlight the importance of long-term groundwater monitoring, salinity-risk management, advanced treatment for drinking use, and controlled irrigation practices to protect soil and water resources in arid aquifer systems.

1. Introduction

Groundwater is a critical global resource, serving as the primary source of freshwater for drinking, agricultural, and industrial purposes in many parts of the world [1]. It is estimated that approximately one-third of the global population relies on groundwater for domestic use [2], with over a billion people directly dependent on these resources in Asia alone [3]. In recent decades, the intensified exploitation of aquifers, driven by rapid population growth, agricultural expansion, and urbanization, coupled with severe drought episodes linked to climate change, has exacerbated water scarcity [4]. This challenge is particularly acute in arid and semi-arid regions like Iran, where surface water is severely limited. Consequently, the sustainable management of groundwater resources in these regions necessitates a rigorous assessment of both water quantity and quality [5].

The quality of groundwater is governed by a complex interplay of natural hydrogeochemical processes and anthropogenic activities. Factors such as the geological framework, aquifer mineralogy, groundwater residence time, and water-rock interactions dictate the natural baseline chemistry, while land-use practices introduce additional contaminants [6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16]. For domestic and agricultural applications, the suitability of groundwater is largely determined by the concentration and composition of dissolved salts [17]. In irrigation, while trace amounts of specific dissolved minerals-originating from the natural weathering of rocks such as limestone and gypsum-are present, the excessive accumulation of these salts can severely compromise soil structure [17].

The continuous deterioration of groundwater quality poses profound threats to both environmental stability and public health. The application of highly saline or sodic water in agriculture can degrade soil fertility, diminish crop yields, and threaten food security [18, 19, 20]. Furthermore, the long-term consumption of heavily mineralized water carries substantial human health risks [1, 21].

To effectively manage these risks, various hydrochemical indices and standard classifications have been established to evaluate groundwater suitability, including sodium percentage (Na%), sodium adsorption ratio (SAR), residual sodium carbonate (RSC), the permeability index (PI), and frameworks like the US Salinity Laboratory (USSL) and Wilcox classifications [22, 23, 24, 25, 26, 27, 28, 29, 30]. Utilizing these established strategies enables researchers and policymakers to monitor potential pollution, avoid redundant data analysis, and implement effective water resource management plans [31, 32]. Building upon this framework, the present study aims to conduct a comprehensive hydrochemical evaluation of groundwater in the arid Yazd-Ardakan plain of Iran, assessing its spatial distribution and suitability for both drinking and agricultural uses.

Although groundwater quality has been widely investigated in arid and semi-arid regions, many previous studies have mainly focused on short-term assessments or local suitability classifications. Limited attention has been given to the integrated evaluation of long-term groundwater salinization, drinking water limitations, and irrigation-induced soil degradation risks in arid aquifer systems such as the Yazd-Ardakan plain. By using a groundwater dataset covering the period from 2002 to 2018, this study provides a broader hydrochemical perspective on salinity development and groundwater quality deterioration in a water-stressed environment. Beyond its local relevance, the findings can support salinization monitoring, irrigation water management, and soil protection strategies in other arid and semi-arid regions facing similar groundwater quality challenges.

2. Materials and methods

2.1 Description of the study area

The study area is located in the Yazd-Ardakan plain, situated within the dry belt of Iran’s central plateau. The region covers an area of approximately 110 km², geographically bounded between longitudes 54°16' to 54°26' E and latitudes 31°49' to 31°57' N, with a central coordinate of 31°53'50" N and 54°22'3" E (Fig. 1). This plain is the largest agricultural producer in Yazd province and accommodates over 70% of the city's population, totaling approximately 526,276 inhabitants [33].

The area is characterized by a hot, arid desert and semi-desert climate heavily influenced by a subtropical high-pressure system. It experiences scarce and irregular rainfall, low relative humidity (30–50%), and extreme evaporation rates ranging from 220 to 3200 mm, characterizing its desert and semi-desert climate. High temperature fluctuations are common, with the first frost typically occurring in mid-November and lasting until mid-March. The average monthly sunshine duration ranges from 124 hours in January to 368 hours in July.

Wind patterns in the region are highly seasonal; northwestern winds prevail during spring and summer, shifting to southeastern winds from November to February, and western winds during March and October. Consequently, the region is subjected to severe environmental and physical challenges, including approximately 50 dusty days annually, the majority of which occur during the summer months [34].

To provide a comprehensive assessment of the groundwater resources supporting this region, 142 groundwater samples were collected from 10 deep monitoring wells (W1–W10) distributed across the study area between 2002 and 2018. The sampling locations were selected to ensure adequate spatial coverage and to represent various geological and land-use settings.

2.2 Chemical analysis

The following water quality parameters were analyzed for each sample: calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), potassium (K^{+}), bicarbonate (HCO_3^{-}), sulfate (SO_4^{2-}), chloride (Cl^{-}), total dissolved solids (TDS), electrical conductivity (EC), and pH. Cations were analyzed using atomic absorption spectrophotometry, bicarbonate was measured by titration, and sulfate and chloride were determined using ion chromatography (IC). The pH and EC were measured at the sampling site using portable meters, and TDS was estimated by the gravimetric method.

3. Results and discussion

The groundwater samples collected from the study area were analyzed for their chemical and physical constituents to assess their suitability for drinking and agricultural use based on World Health Organization guidelines [35] and Iranian standards [36]. The Physico-chemical characterization of groundwater samples is given in Table 3.

3.1 Suitability for drinking

Understanding the quality of groundwater is crucial as it determines its suitability for various purposes including drinking and agricultural uses. The analysis is based on data from 10 sampling stations (W1–W10) (Table 3).

pH

pH measures the hydrogen ion concentration and indicates water's acidity or alkalinity. The WHO acceptable range for drinking water is 6.5–8.5. The study area pH ranges from 6.19 to 8.22 with a mean of 7.60. Most samples fall within the acceptable range, indicating generally neutral to slightly alkaline conditions suitable for drinking water.

Electrical Conductivity (EC)

Electrical conductivity indicates the total dissolved salts in water and is a measure of water's ability to conduct electric current. The World Health Organisation (WHO) guidelines for drinking water is 1400 µS/cm. In the study area, EC ranges from 1687 µS/cm to 21422 µS/cm with a mean of 6464.20 µS/cm Most sampling stations(W1-W10) exceed the WHO limit, with particularly high values at stations W5,W6,W8,W9 and W10, indicating significant mineralization and potential water quality concerns.

Total Dissolved Solids (TDS)

TDS represents the total concentration of dissolved substances in water. WHO identifies increasing palatability problems above approximately 1000 mg/L, but does not establish a health-based guideline value for TDS [37]. The study area shows TDS values ranging from 1080 to 13,924 mg/L with a mean of 4186.61 mg/L. All samples exceed the 1000 mg/L desirable value in ISIRI [36]; the maximum permissible value in that edition is 1500 mg/L. Stations W5, W6, W8, W9, and W10 show particularly high concentrations. The literature-based TDS classification is presented in Table 1.

Table 1
Classification of groundwater based on total dissolved solids (TDS) [38, 39]

TDS range (mg/L)	Water type	Number of samples	% of samples	Interpretation
< 500	Desirable for drinking	0	0.00	No sample falls within the desirable drinking-water range
500–1000	Permissible for drinking	0	0.00	No sample falls within the permissible drinking-water range
1000–3000	Useful for irrigation	73	51.41	Moderately saline water; generally more suitable for irrigation than direct drinking
> 3000	Unfit for drinking and irrigation	69	48.59	Highly saline water; unsuitable without treatment or strict management
Total		**142**	**100.00**	

Sodium (Na^+)

Sodium is a major cation with a WHO guideline of 200 mg/L for drinking water. The study area exhibits sodium concentrations from 156.4 to 4346.77 mg/L with a mean of 990.62 mg/L. Most stations significantly exceed the WHO limit, particularly W5, W6, W8, W9, and W10, indicating potential health risks for individuals with hypertension or cardiovascular conditions.

Chloride (Cl^-)

Chloride affects taste and corrosivity with a WHO guideline of 250 mg/L. The study area exhibits chloride concentrations from 335.48 to 6647.38 mg/L with a mean of 1738.07 mg/L. All stations significantly exceed the WHO limit, with extremely high values at stations W5, W6, W8, W9, and W10. In this arid, inland region, these elevated chloride levels can be primarily attributed to the dissolution of evaporite minerals (such as halite) in the aquifer matrix, high evaporation rates, and potential industrial or agricultural wastewater contamination.

Magnesium (Mg^{2+})

Magnesium contributes to water hardness with a WHO guideline of 150 mg/L [35]. The study area shows magnesium levels ranging from 35.04 to 483 mg/L with a mean of 155.44 mg/L. Stations W1, W3, W5, W6, W8, W9, and W10 exceed the WHO limit, contributing to water hardness and potential health concerns at higher concentrations.

Calcium (Ca^{2+})

Calcium is an essential nutrient with a WHO guideline of 200 mg/L for drinking water. In the study area, calcium concentrations range from 73.4 to 606.8 mg/L with a mean of 237.73 mg/L. Several stations (W3, W4, W5, W6, and W10) exceed the WHO limit, indicating hard water conditions that may cause scaling in pipes and affect taste.

Bicarbonate (HCO_3^-)

Bicarbonate acts as a buffer in natural waters and contributes to alkalinity. There's no specific WHO limit, but typical ranges are 50–300 mg/L. The study area shows bicarbonate concentrations from 122 to 302.56 mg/L with a mean of 220.08 mg/L, indicating normal buffering capacity in most samples.

Potassium (K^+)

Potassium is generally not regulated in drinking water as it's an essential nutrient. The study area shows potassium levels ranging from 0.78 to 15.99 mg/L with a mean of 4.45 mg/L. These concentrations are within normal ranges and pose no health concerns.

Sulfate (SO_4^{2-})

Sulfate is a major anion with a WHO guideline of 250 mg/L for drinking water. The study area shows sulfate concentrations ranging from 165.12 to 2735.52 mg/L with a mean of 762.12 mg/L. Most stations exceed the WHO limit, particularly W5, W6, W8, W9, and W10, which may cause gastrointestinal effects and contribute to water hardness.

Based on the comprehensive chemical analysis of water samples from the ten monitoring stations (W1-W10), the water in this study area is generally unsuitable for drinking purposes without treatment. All stations show excessive total dissolved solids (TDS) levels well above the WHO limit of 1000 mg/L, with values ranging up to 13,924 mg/L, indicating severe mineralization. Critical concerns include significantly elevated chloride concentrations (up to 6,647 mg/L), high sulfate content exceeding WHO guidelines and excessive calcium and magnesium levels contributing to water hardness. While pH levels remain within acceptable ranges and potassium concentrations pose no health concerns, the overall water quality is compromised by high salinity and mineral content. The water requires comprehensive treatment, including desalination or reverse osmosis, before it can be

considered safe for human consumption, with stations W5, W6, W8, W9, and W10 showing particularly poor water quality. A comparison of the measured groundwater quality parameters with WHO and Iranian drinking water standards is presented in Table 2.

Table 2
Measured groundwater parameters in relation to WHO guidance [35] and Iranian Standard 1053 [36]

No.	Water quality parameter	Unit	WHO international standards [35]		Iran standards [36]		Range in the study area	Quality status
			Most desirable limit	Max. allowable limit	Highest desirable	Max. permissible		
1	pH	-	6.5	8.5	6.5	8.5	6.19–8.22	Mostly acceptable; some samples below 6.5
2	EC	µS/cm	1400	-	1000	2000	1687–21422	Mostly above desirable/permissible limits
3	TDS	mg/L	500	1500	-	-	1080–13924	Above desirable; many samples unsuitable
4	Ca^{2+}	mg/L	75	200	-	-	73.4–606.8	Partly exceeds drinking limits
5	Mg^{2+}	mg/L	50	150	-	-	35.04–483	Partly exceeds drinking limits
6	Na^{+}	mg/L	-	200	-	-	156.4–4346.7	Mostly above WHO limit
7	K^{+}	mg/L	-	12	-	-	0.78–15.99	Mostly acceptable; some samples exceed limit
8	HCO_3^{-}	mg/L	-	-	-	-	122–302.56	No specific guideline limit
9	SO_4^{2-}	mg/L	200	400	250	400	165.12–2735.52	Partly to strongly above limits
10	Cl^{-}	mg/L	200	600	-	-	335.48–6647.38	Above desirable; often above allowable limit

Note: EC is expressed as µS/cm; all ionic concentrations are expressed as mg/L. "-" indicates that no limit was specified in the cited standard.

3.2 Hydrochemical facies

The groundwater in the Yazd Ardakan area has been analyzed using the Piper trilinear diagram to understand its geochemical characteristics (Fig. 2) [40]. This diagram helps classify water types based on the relative concentrations of major cations and anions. The analysis shows that the groundwater samples vary in their chemical composition. According to the Piper diagram, the groundwater in the Yazd Ardakan region predominantly falls within the Chloride-Sulfate facies, indicating that chloride and sulfate are the dominant anions present. Within this Chloride-Sulfate facies, there is also a Chloride-Sulfate-Calcium facies, characterized by calcium as the major cation. This facies occupies a significant portion of the diagram, suggesting it is a common water type in the region. Additionally, a Chloride-Sulfate-Sodium facies is characterized by sodium as the dominant cation, represented by a cluster of samples towards the right side of the diagram. Lastly, the Mixed Chloride-Sulfate-Calcium-Magnesium facies shows a significant presence of both calcium and magnesium as major cations, located in the central region of the diagram. The dominance of chloride and sulfate in the groundwater suggests the influence of saline sources, likely due to geological formations or anthropogenic activities. The presence of calcium and magnesium indicates the dissolution of carbonate and silicate minerals in the aquifer.

Table 3
Physico-chemical characterization of groundwater samples of the study area

Acronym	Station name	Statistic	EC (µS/cm)	TDS (mg/L)	pH	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Na^{+} (mg/L)	K^{+} (mg/L)	HCO_3^{-} (mg/L)	Cl^{-} (mg/L)	SO_4^{2-} (mg/L)
W1	Zarch	Maximum	5380.00	4000.00	7.85	214.60	158.64	850.31	7.80	273.28	1431.72	720.00
		Minimum	4770.00	3050.00	6.19	91.80	85.20	700.35	1.56	190.32	1201.32	449.76
		Mean	5087.20	3320.93	7.45	173.31	121.82	767.03	3.93	230.86	1305.29	559.30
		SD	171.29	236.44	0.41	29.65	22.08	44.01	1.96	31.59	65.38	86.81
		No. Sample	15	15	15	15	15	15	15	15	15	15
W2	Charkhan	Maximum	2272.00	1412.00	8.02	127.80	72.96	300.15	3.90	292.80	410.38	350.40
		Minimum	1687.00	1080.00	7.15	73.40	35.04	189.98	1.17	195.20	335.48	180.00
		Mean	1934.24	1233.76	7.54	106.86	56.61	221.25	1.84	264.31	365.07	255.73
		SD	192.50	116.95	0.26	15.20	9.76	34.85	0.64	28.08	24.68	60.10
		No. Sample	17	17	17	17	17	17	17	17	17	17
W3	Khazer Abad	Maximum	6520.00	4100.00	8.07	606.80	284.04	300.15	3.90	229.36	2122.19	480.00
		Minimum	2322.00	1486.00	7.17	151.60	69.12	156.40	0.78	170.80	415.35	165.12
		Mean	3427.80	2240.60	7.59	270.25	131.03	244.87	2.08	202.24	872.85	356.42
		SD	1337.78	831.90	0.21	153.34	74.27	38.74	0.88	16.48	533.88	85.83
		No. Sample	15	15	15	15	15	15	15	15	15	15
W4	Darvaze Quran	Maximum	5220.00	3340.00	8.07	239.60	165.72	780.39	5.85	292.80	1371.37	1499.04
		Minimum	2324.00	1676.00	7.00	151.80	66.24	260.13	1.95	146.40	390.50	399.84
		Mean	3327.00	2139.20	7.60	182.65	98.44	395.51	2.96	193.57	669.70	614.21
		SD	954.68	598.66	0.27	27.38	30.49	178.24	1.30	41.60	353.07	252.80
		No. Sample	15	15	15	15	15	15	15	15	15	15
W5	Kilometer 5 Jadde Yazd-Ardakan	Maximum	17510.00	11212.00	8.22	463.00	483.00	2901.22	14.04	262.30	5581.31	1998.72
		Minimum	12150.00	7290.00	7.26	271.40	246.24	2050.91	7.80	212.28	3253.58	999.36
		Mean	14317.10	9007.00	7.77	360.88	329.53	2390.99	10.22	240.10	4262.13	1419.02
		SD	1912.63	1283.98	0.27	67.00	79.61	300.89	2.47	17.67	875.33	330.67
		No. Sample	10	10	10	10	10	10	10	10	10	10
W6	Jadde Yazd-Ardakan	Maximum	11920.00	8562.00	8.20	399.20	352.80	2200.87	12.87	287.92	3654.02	1499.04
		Minimum	9282.00	5582.00	7.42	207.60	208.32	1596.20	3.90	209.84	2726.40	998.40
		Mean	11017.64	7197.55	7.76	316.02	255.31	1860.47	8.51	253.87	3182.03	1241.11
		SD	737.89	730.65	0.24	65.50	56.16	194.05	2.95	26.96	247.65	233.22
		No. Sample	11	11	11	11	11	11	11	11	11	11
W7	Abrand Abad	Maximum	2860.00	1830.00	7.88	161.20	108.84	350.06	3.90	273.28	525.76	549.60
		Minimum	2250.00	1440.00	7.12	123.80	61.56	220.11	1.17	130.54	434.52	300.00
		Mean	2490.53	1615.24	7.58	149.35	77.84	263.80	2.09	191.76	479.21	421.92
		SD	160.54	98.21	0.25	9.64	10.40	29.74	0.92	31.50	25.96	61.10
		No. Sample	17	17	17	17	17	17	17	17	17	17

Acronym	Station name	Statistic	EC (µS/cm)	TDS (mg/L)	pH	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Na^{+} (mg/L)	K^{+} (mg/L)	HCO_3^{-} (mg/L)	Cl^{-} (mg/L)	SO_4^{2-} (mg/L)
W8	Kheyre Abad	Maximum	6580.00	4450.00	8.20	271.40	170.40	950.36	8.97	302.56	1731.69	801.60
		Minimum	3030.00	1940.00	7.09	171.60	94.68	169.97	0.78	170.80	410.38	499.20
		Mean	5029.07	3256.73	7.61	221.99	148.40	649.52	3.69	231.11	1217.41	637.18
		SD	1238.01	841.54	0.29	28.99	18.82	273.02	2.37	37.55	429.43	91.61
		No. Sample	15	15	15	15	15	15	15	15	15	15
W9	Boulevare Jumhuri	Maximum	4780.00	3050.00	8.00	370.00	253.20	620.31	5.85	297.68	931.17	1174.08
		Minimum	3373.00	2246.00	7.08	239.60	130.20	218.50	0.78	175.68	580.78	499.68
		Mean	4288.15	2754.77	7.64	288.17	170.89	349.65	2.70	232.36	786.54	887.63
		SD	455.31	258.07	0.21	43.07	34.88	104.75	1.67	48.63	114.98	163.53
		No. Sample	13	13	13	13	13	13	13	13	13	13
W10	Sath Shahr	Maximum	21422.00	13924.00	7.94	479.00	435.60	4346.77	15.99	219.60	6647.38	2735.52
		Minimum	17230.00	11220.00	7.24	223.60	179.88	3243.00	5.07	122.00	5506.05	1449.12
		Mean	19251.36	12617.79	7.56	417.74	283.29	3760.53	10.36	172.67	5973.23	1772.33
		SD	975.73	606.71	0.22	70.48	64.95	319.67	3.29	36.52	333.05	373.16
		No. Sample	14	14	14	14	14	14	14	14	14	14
Total	All stations	Maximum	21422.00	13924.00	8.22	606.80	483.00	4346.77	15.99	302.56	6647.38	2735.52
		Minimum	1687.00	1080.00	6.19	73.40	35.04	156.40	0.78	122.00	335.48	165.12
		Mean	6464.20	4186.61	7.60	237.73	155.44	990.62	4.45	220.08	1738.07	762.12
		SD	5504.31	3582.84	0.28	112.87	94.22	1130.19	3.66	43.09	1808.66	507.42
		No. Sample	142	142	142	142	142	142	142	142	142	142

3.3 Suitability for agriculture

Parameters like sodium percentage (Na%), sodium adsorption ratio (SAR), Residual Sodium Carbonate (RSC), and permeability index (PI) serve as crucial salinity indicators for assessing groundwater quality and its appropriateness for irrigation purposes (Table 4). The EC–SAR classification is shown in Fig. 3, and the EC–Na% classification is shown in Fig. 4. It is important to note that prior to calculating these agricultural indices, the ionic concentrations of all groundwater samples were converted from milligrams per liter (mg/L) to milliequivalents per liter (meq/L).

Sodium Percentage (Na%)

Sodium percentage (Na%) is an important indicator of dissolved sodium levels in groundwater, which is essential for assessing sodium-related risks associated with irrigation. The sodium percentage is calculated using the following equation

$$Na\% = \frac{Na * 100}{Ca + Mg + Na + K}$$

Where all ionic concentrations are expressed in meq/L.

Salts in irrigation water can negatively impact plants and compromise soil structure by reducing permeability and aeration, ultimately affecting plant development. When the Na% exceeds 60%, sodium can accumulate in the soil, leading to a significant decline in its physical properties. Based on the sodium percentage classification, only 2.82% of the samples (4 samples) fall into the excellent category (Na% < 20). About 14.08% of the samples (20 samples) are classified as good quality, with Na% ranging from 20 to 40. The majority of the groundwater samples, accounting for 45.77% (65 samples), fall within the permissible limit (Na% between 40 and 60). However, a significant portion of the samples indicates potential sodium hazards, with 35.21% (50 samples) classified as doubtful (Na% between 60 and 80) and 2.11% (3 samples) categorized as unsuitable (Na% > 80) for irrigation purposes. Furthermore, the high overall electrical conductivity of all samples, which ranges from 1687 to 21,422 µS/cm, exacerbates these sodium-related risks, placing the majority of the groundwater in high salinity hazard zones. The classification of irrigation water quality based on total salt concentration and sodium percentage is shown in Fig. 4.

Sodium Adsorption Ratio (SAR): (Fig. 3)

$$\mathrm{SAR} = \frac{\mathrm{Na}^{+}}{\sqrt{\frac{\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}}{2}}}$$

Based on the SAR classification (Table 4), 64.08% of the water samples (91 samples) are classified as S1 (low sodium hazard), with SAR values of less than 10. These waters are highly suitable for irrigation, presenting minimal risk of sodium-related soil degradation. About 14.79% of the samples (21 samples) fall into the S2 (medium sodium hazard) category, with SAR values ranging from 10 to 18. While generally appropriate for irrigation, caution may be required when applying these waters to fine-textured soils with a high cation-exchange capacity. Approximately 11.27% of the samples (16 samples) are designated as S3 (high sodium hazard), with SAR values between 18 and 26. These waters can potentially lead to elevated levels of exchangeable sodium in various soils, which necessitates specific soil management practices. Finally, 9.86% of the samples (14 samples) are classified as S4 (very high sodium hazard), with SAR values exceeding 26. These waters are generally unsuitable for irrigation under standard conditions.

Residual Sodium Carbonate (RSC)

Beyond SAR and sodium percentage, the surplus amount of carbonate and bicarbonate ions in groundwater relative to calcium and magnesium concentrations also affects the groundwater's suitability for irrigation use. This parameter is referred to as residual sodium carbonate (RSC) and is determined using the following calculation

$$RSC = (CO_3^{2-} + HCO_3^{-}) - (Ca^{2+} + Mg^{2+})$$

.

Where the concentrations are reported in meq/L

The Residual Sodium Carbonate (RSC) assessment yields the most favorable results (Table 4), with all 142 samples (100%) classified as good quality, indicating that carbonate and bicarbonate concentrations do not pose irrigation concerns in this study area.

The Permeability Index (PI)

The permeability index results similarly demonstrate that the groundwater is appropriate for agricultural purposes. This index is expressed as follows

$$PI = \frac{\left(\varvec{N}\varvec{a}^{+} + \sqrt{\varvec{H}\varvec{C}\varvec{O}_3^{-}}\right)\varvec{*}100}{(\varvec{C}\varvec{a}^{2+} + \varvec{M}\varvec{g}^{2+} + \varvec{N}\varvec{a}^{+})}$$

.

Where the concentrations are reported in meq/L.

The Permeability Index (PI) (Table 4) shows predominantly positive results, with 97.18% of samples falling within excellent to good categories, suggesting that groundwater permeability characteristics are generally suitable for irrigation purposes, with only 2.82% of samples showing injurious effects.

Table 4
Classification of groundwater quality for irrigation suitability

Parameter	Range	Water quality	Number of samples	% of Samples
SAR	< 10	Excellent (low sodium water S1)	91	64.08
	10–18	Good (medium sodium water S2)	21	14.79
	18–26	Doubtful (high sodium water S3)	16	11.27
	> 26	Unsuitable (very high sodium water S4)	14	9.86
%Na	< 20	Excellent	4	2.82
	20–40	Good	20	14.08
	40–60	Permissible	65	45.77
	60–80	Doubtful	50	35.21
	> 80	Unsuitable	3	2.11
RSC	< 1.25	Good	142	100.00
	1.25–2.5	Doubtful	0	0.00
	> 2.5	Unsuitable	0	0.00
PI	> 75	Excellent	15	10.56
	75 > PI > 25	Good	123	86.61
	< 25	Injurious	4	2.82

Figure 3 Classification of irrigation water quality concerning electrical conductivity (EC) and sodium hazard (SAR)

Figure 4 Classification of irrigation water quality concerning total salt concentration and sodium percentage

4. Conclusion

This study evaluated the hydrochemical characteristics, drinking water suitability, and irrigation-related salinization risks of groundwater in the arid Yazd-Ardakan plain, central Iran. The results indicate that groundwater quality in the study area is strongly affected by salinization, as reflected by high EC, TDS, chloride, sulfate, and sodium concentrations. The dominant Chloride-Sulfate hydrochemical facies further confirms the influence of salinity-related processes on groundwater chemistry.

From a drinking water perspective, the groundwater is generally unsuitable for direct human consumption. All analyzed samples had TDS concentrations above 1000 mg/L, indicating the palatability limitation described by WHO, and several stations, particularly W5, W6, W8, W9, and W10, showed critically poor water quality. Therefore, the use of this groundwater for drinking purposes requires advanced treatment processes, such as desalination or reverse osmosis, before consumption.

For irrigation use, the results showed a more complex pattern. Although many samples had acceptable SAR values and favorable RSC and PI conditions, the high sodium percentage in a large proportion of samples indicates a considerable risk of long-term soil structure degradation, reduced permeability, and salinity accumulation. Therefore, the agricultural use of groundwater in this region should be accompanied by careful irrigation management, appropriate drainage, soil monitoring, leaching practices, and the selection of salt-tolerant crops.

Overall, the findings highlight the importance of continuous groundwater quality monitoring and salinity-risk management in arid aquifer systems. The Yazd-Ardakan plain represents a typical water-stressed environment where groundwater deterioration can simultaneously threaten drinking water safety, agricultural sustainability, and soil health. The results of this study can support local water resource planning and may also provide useful insights for managing groundwater salinization and irrigation-related soil degradation in other arid and semi-arid regions facing similar environmental pressures.

Declarations

Funding
No funding was received for conducting this study.

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Data Availability

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

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Figures

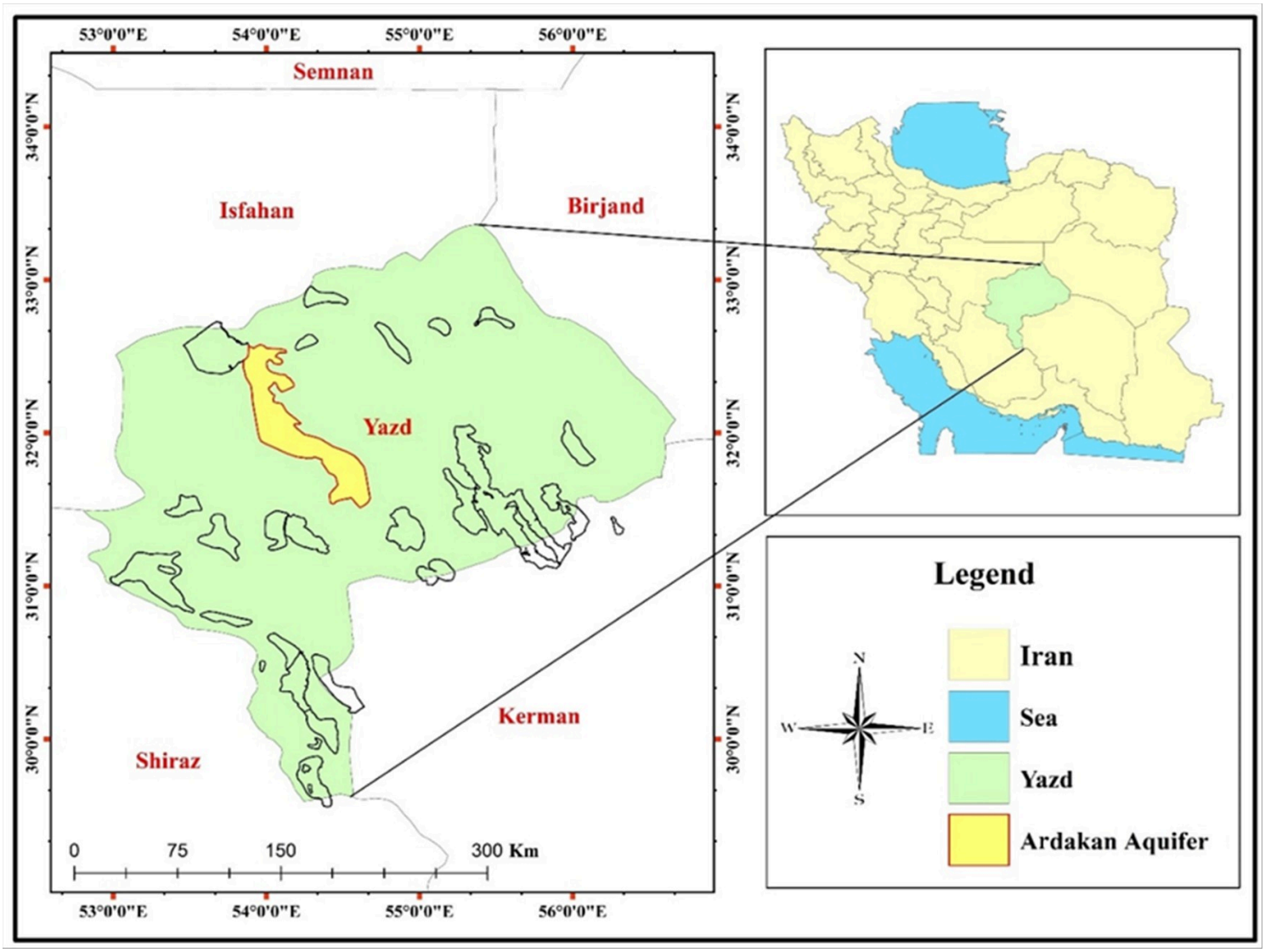

Figure 1

The geographical position of the study area

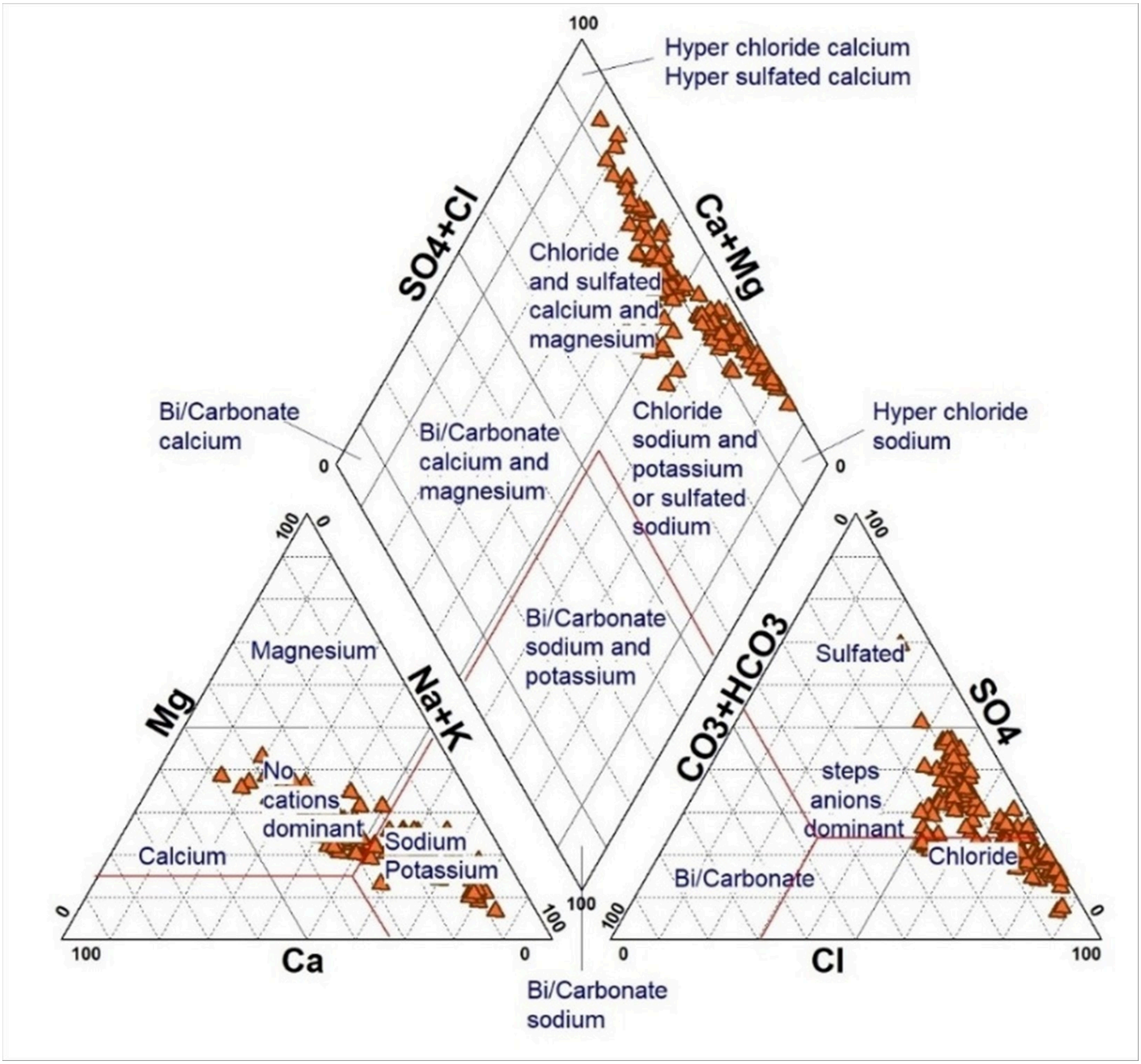

Figure 2

Piper diagram showing the hydrochemical facies of groundwater samples in the Yazd-Ardakan plain

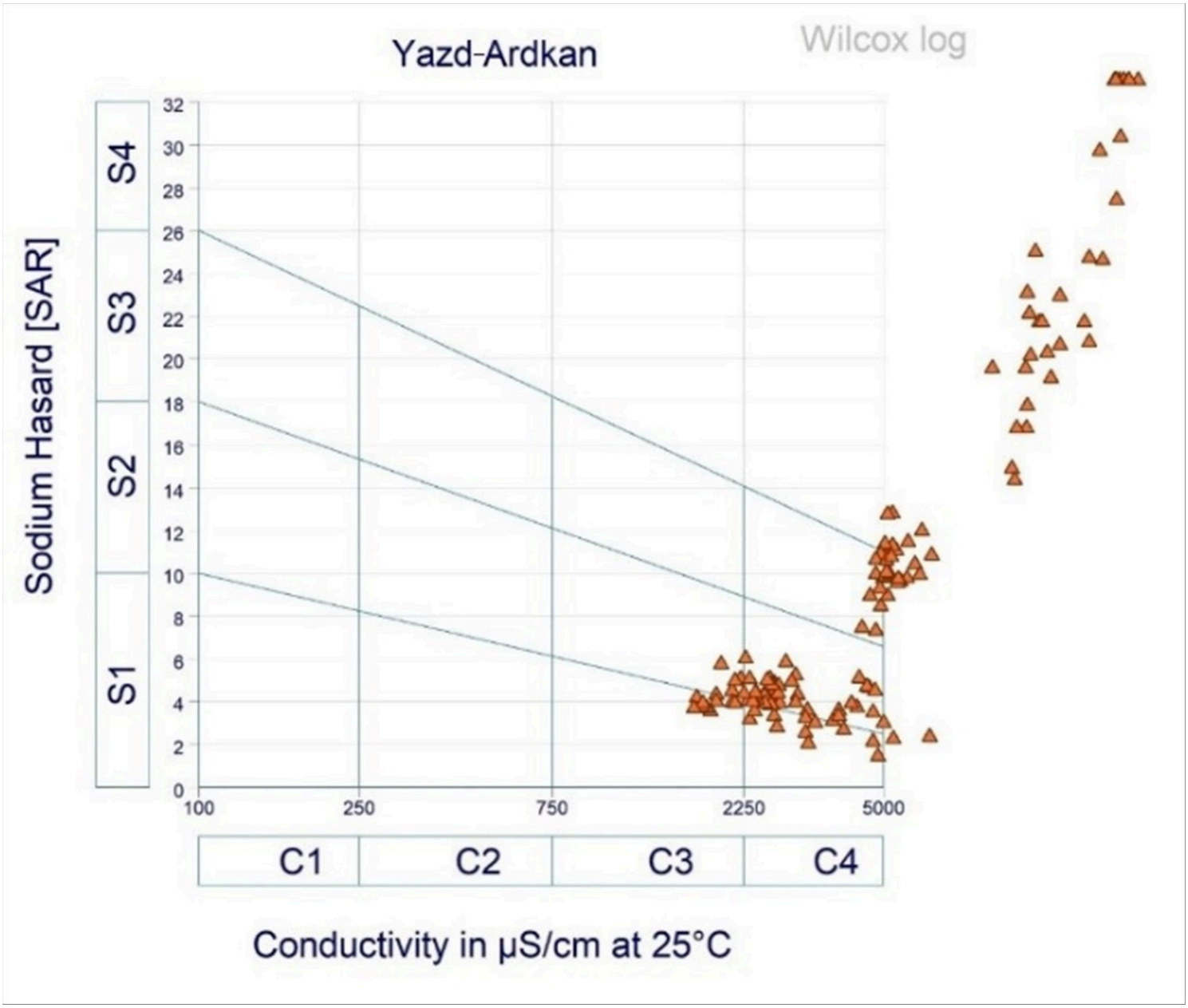

Figure 3

Classification of irrigation water quality concerning electrical conductivity (EC) and sodium hazard (SAR)

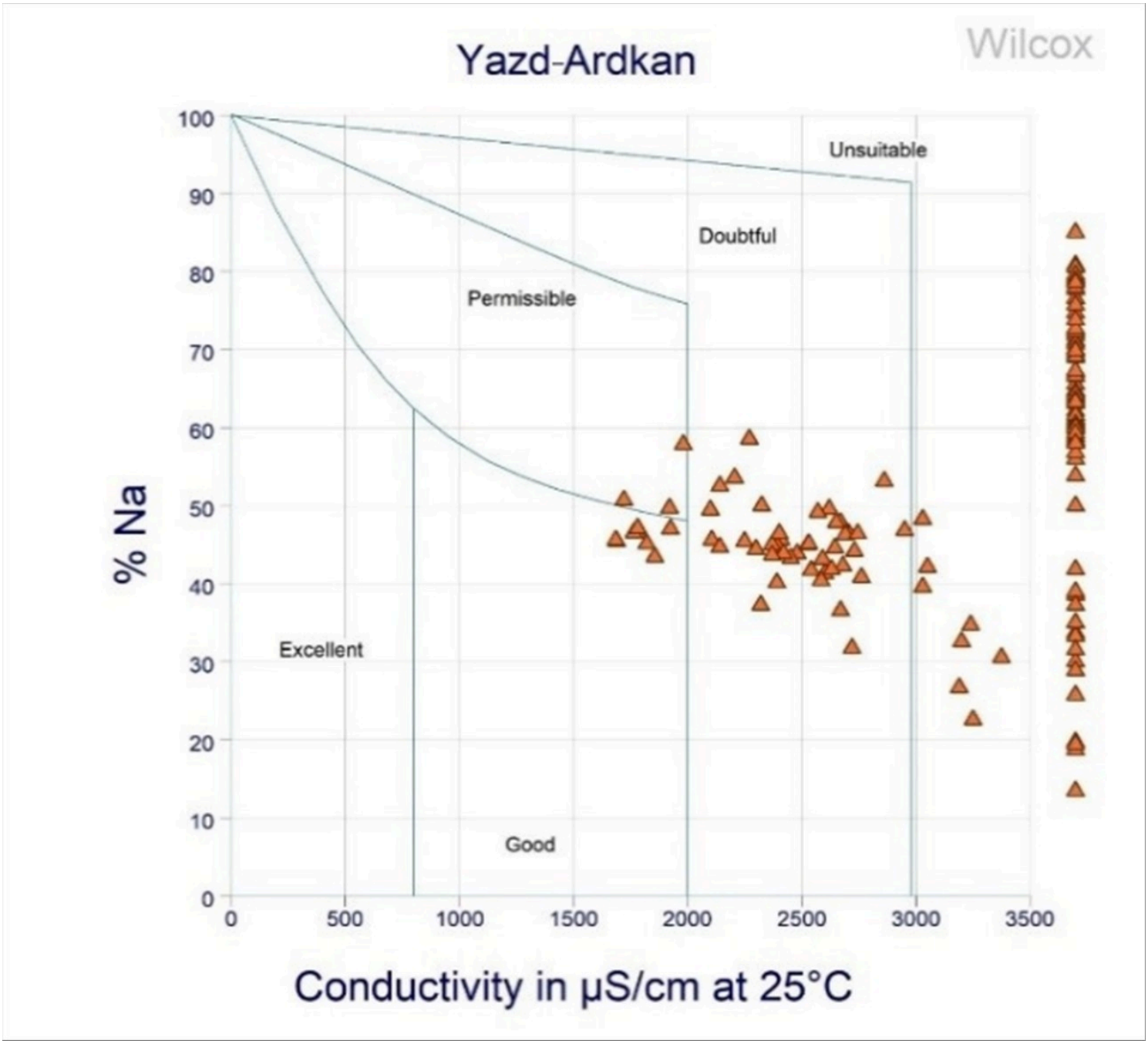

Figure 4

Classification of irrigation water quality concerning total salt concentration and sodium percentage