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Evaluation and Zoning of Groundwater Quality for Agricultural Purposes in Gonabad Plain Arid Region

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Abstract

Groundwater is one of the most important water resources for human society, particularly in arid and semi-arid regions. It is estimated that groundwater supplies 34% of drinking water, 42% of irrigated agricultural water, and 24% of direct industrial use worldwide. In arid regions, where average rainfall is significantly low and its distribution is uneven, groundwater plays a crucial role in agricultural water supply. This aim of this work is to evaluate the groundwater quality of the Gonabad Plain in the Khorasan Razavi Province for agricultural purposes using the standards of the Food and Agriculture Organization (FAO); the standards of the Iranian Institute of Standards and Industrial Research, irrigation indices, and the Wilcox classification over a 15-years period. For this purpose, 10 chemical parameters of water including calcium, magnesium, sodium, sodium adsorption ratio (SAR), Electrical Conductivity (EC), Total Dissolved Solids (TDSs), pH, bicarbonate, chloride, and sulfate were analyzed between 2007 and 2022 in 16 wells within the plain. Based on the FAO standards, two parameters of electrical conductivity and magnesium exceeded the permissible limits. According to irrigation indices, the water was classified as unsuitable for drip and sprinkler irrigation, due to certain limitations. Furthermore, based on the Wilcox classification, 31.25% of the wells contained water of medium quality for agricultural use, while the rest were deemed unsuitable, requiring remedial measures.

1. Introduction

Water, as an essential element, has held a pivotal role in human life throughout history (Shiklomanov, 1998). Freshwater resources including rivers, lakes, and groundwater have been crucial in meeting human needs for drinking, agriculture, and industry (Jain et al., 2007). These resources have not only served as vital lifelines for sustaining human life and livelihoods, but have also played a fundamental role in the formation and development of civilizations(Chandrakar et al., 2024). Many of the world's great cities and civilizations historically emerged near rivers (Abedi Koupai & Babaiee, 2019) and groundwater sources, with these resources ensuring their growth and sustainability (Hosseiny et al., 2021). However, with population growth and societal development, pressure on freshwater resources has intensified, leading to challenges such as the degradation of both the quality and quantity of these resources, particularly in arid and semi-arid regions (Motamedi Rad et al., 2021) Iran, as a country characterized by arid and semi-arid climates, faces significant challenges in water resource management (Ghomishoun et al., 2012; Khatibi & Arjjumend, 2019; Madani, 2014). The water resources comprising surface and groundwater each have distinct features and limitations. Surface water, which includes rivers, lakes, and wetlands, is under considerable stress due to decreasing rainfall, climate change, and mismanagement (Sharifi et al., 2021; Yazdandoost & Moradian, 2021). Many rivers in Iran exhibit seasonal flow patterns. Groundwater, long-recognized as a primary source for drinking and agricultural water supply, is now facing severe pressure due to excessive annual withdrawals, threatening its sustainability (Hosseini et al., 2016). This over-extraction has resulted in a decline in aquifer reserves, exacerbating the strain on available resources (Safdari et al., 2022). This issue is particularly critical in Iran’s dry and low-rainfall regions, where dependence on groundwater is greater. The increase in groundwater extraction in Iran can be attributed to several key factors. A rapid population growth and the corresponding rise in water demand for domestic consumption and agriculture are among the primary reasons, as the majority of the water resources are used for agricultural purposes (Alizadeh & Keshavarz, 2005). Additionally, decreasing rainfall and climate change have severely impacted surface water resources, forcing farmers to rely more on groundwater. Furthermore, the rapid development of urban areas and industrial activities has significantly increased the demand for water to meet municipal and production needs (Bates et al., 2008). Collectively, these factors have led to unsustainable and excessive withdrawals from groundwater resources. The over-extraction of groundwater in recent years has placed immense pressure on aquifers. This excessive withdrawal has not only lowered groundwater levels but also adversely affected water quality. Water quality refers to the characteristics of water resources that influence their suitability for specific uses. Different uses require varying quality standards, and water with fewer issues or better results compared to another source is considered to have superior quality. Groundwater quality is as crucial as its quantity for its usability across different applications. It is shaped by all processes and reactions that occur from the time water shrinks in the environments to when it arises from wells and Qanats (Sedaghat, 1999). Assessing water quality involves analyzing its physical characteristics (temperature, color, taste and odor, turbidity, and suspended solids), chemical components (salts and dissolved ions), biological properties (bacteria, viruses, protozoa, and parasitic worms), and ecological aspects (relationships between water components and living and non-living organisms within the water cycle).

Groundwater serves as a critical resource for meeting agricultural, domestic, and industrial demands, underscoring the urgency of evaluating its quality. The increasing pressures on water resources, coupled with the growing risk of quality deterioration - particularly in arid and semi-arid regions- highlight the pressing need for precise and targeted research. Such studies, focusing on the systematic analysis and evaluation of groundwater quality in high-stress areas, are essential for advancing effective water resource management practices and addressing potential threats before they escalate(Ashouri et al., 2024; Emamgholizadeh et al., 2014).

Numerous studies have been conducted to evaluate groundwater quality using various methods. For instance, Salari investigated the groundwater quality of the Shiraz Plain using water quality indices for agricultural, drinking, and industrial purposes. The results obtained from the Wilcox and Schuler quality indices indicated that the groundwater was of moderate quality for agricultural use and acceptable for drinking purposes. Additionally, based on the Langelier Saturation Index, the water source was reported to range from corrosive to scale-forming (Salari, 2024). Mesbahzadeh et al. conducted a study on the Khwash Plain aquifer; their results indicated that most of the wells in the region ranged from saline to highly saline, making their use for agriculture harmful or requiring specific remedial measures (MESBAHZADEH & Soleimani Sardou, 2018). Motamedi Rad et al (2021) evaluated the quality of karst aquifer water resources in Rooyin, Esfarayen, located in the North Khorasan Province. Their findings, based on the Wilcox index, revealed that 15% of the springs contained saline water but were still usable for agriculture, while the remaining springs were classified as suitable for agricultural purposes (Motamedi Rad et al., 2021). Soda et al. conducted a study to assess the water quality of the Bashar River for agricultural purposes and the factors influencing its quality characteristics. The results of the Wilcox diagram indicated that the water quality was suitable for agricultural use. However, downstream of the river, water quality for irrigation deteriorated, due to the increase in sodium and electrical conductivity resulting from the discharge of fish farming sewages (Zahra Atash Souda, 2013). In the northwest of Kabudarahang, Hamadan Province an analysis of groundwater quality data and hydrogeochemical maps revealed that the water quality was suitable to acceptable for agricultural use (C2S1, C3S1), acceptable for drinking, and corrosive for industrial purposes (Kordi et al., 2014). In the western part of Marivan County, Kurdistan Province, the assessment of water quality based on the Wilcox and Schuler diagrams revealed that the water from most of the studied wells and springs had suitable quality for drinking and irrigation. Additionally, moving from east to west, the concentrations of the parameters decreased (Salehi & Zeinivand, 2014). Jahanshahi et al., conducted a study on the Babak Plain aquifer in Kerman Province. The worst water quality for drinking and agriculture was found in the southern and southeastern areas of the plain, with the severe decline in quality attributed to the presence of a salt crust, which is likely a continuation of the salt crust from the Sirjan Desert (Jahanshahi et al., 2014). The analysis results of the chemical parameters of the water from the wells in the Hashtgerd Plain, Alborz, showed that 99% of the aquifer was classified as good for agricultural use according to the Wilcox index, while 1% was categorized as medium (Malekian & Mirdashtvan, 2015). The results of the groundwater quality assessment in the Malayer Plain, based on the Wilcox index, indicated that the water quality for agricultural use was classified into two categories: good and medium (Sadeghi et al., 2016). A study was conducted to assess the chemical parameters of groundwater for agricultural use in Golestan Province. The results of the Wilcox index indicated that 95% of the area had medium quality, and according to the FAO guidelines, 89% of the area had good to medium water quality. Additionally, using the potential salinity and actual salinity indices, the probability of salinity occurrence in the central and western parts of the plain was found to be higher (Delbari et al., 2016).

Take on precise chemical analyses and classifications aligned with national and international standards, this research work provides a comprehensive evaluation of groundwater quality in the Gonabad plain for agricultural applications. Beyond assessing the current status of groundwater resources, it aims to propose actionable strategies for sustainable management in arid and semi-arid regions. The outcomes of this study are expected to offer a robust framework for informed decision-making and mitigating the negative impacts of overextraction.

Furthermore, the research holds potential as a replicable model for other regions grappling with similar challenges, contributing significantly to the sustainability of groundwater resources.

2. Materials and Methods

2.1. Studied Area

The studied area, Gonabad Plain, is located in the southern part of Khorasan Razavi Province in eastern Iran, as shown in Figure 1. The plain is situated between longitudes 58° 19' to 59° 1' and latitudes 34° 2' to 34° 22'. Gonabad Plain covers an area of 1,103 square kilometers and is classified as a prohibited plain for new wells by the Iran Water Management Company. Gonabad Plain is known for its semi-arid climate, characterized by hot summers and cold winters. The region experiences significant seasonal temperature variations, and precipitation levels are relatively low. This plain is also famous for its unique hydrological features including Qanats, that have been a vital water source for agriculture in the region. The land use of the plain is mainly agriculture. The designation of the plain as prohibited refers to its environmental sensitivities, caused by issues such as water scarcity, land degradation, and the impacts of climate change, necessitating more careful management.

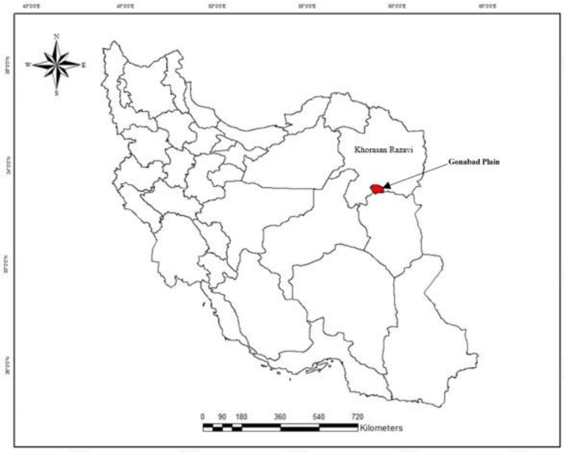


Figure 1. The location of Gonabad Plain in the southern part of Khorasan Razavi Province, highlighted in red on the map of Iran.

2.1.1. Data

For this research work, data from the Khorasan Razavi Regional Water Organization spanning the 15-years period from 2007 to 2022 were utilized. Ten water quality parameters were examined including Ca^{2+} (calcium), Mg^{2+} (magnesium), Na^{+} (sodium), SAR (Sodium Absorption Ratio), EC (Electrical Conductivity), TDS (Total Dissolved Solids), pH (Acidity), HCO_3^{-} (Bicarbonate), Cl^{-} (Chloride), and SO_4^{2-} (Sulfate). These parameters were analyzed from 16 monitoring wells located within the Gonabad Plain. The names and coordinates of the selected wells are presented in Table 1.

Table 1. Names and coordinates of the selected wells.

Number	Well Name	YTUM	XUTM
1	Pasdaran	3803736	654829
2	Alipour	3801198	658699
3	Taghavi	3805042	657492
4	Al-Mahdi	3803263	655656
5	Abdolali	3806112	657722
6	Ansari	3798800	656900
7	Arjmand	3807652	656155
8	Pourebrahim	3799733	652650
9	Alizadeh	3806932	647251
10	Jaddeh Sento	3803563	657907
11	Ahmad Amin	3807827	658815
12	Heidarzadeh	3808730	659001
13	Jaddeh Kakhak	3798336	654396
14	Yaqoubi	3801458	649715
15	Mousa Zadeh	3805638	657728
16	Ghorban Beigi	3804406	657357

2.1.2. FAO Standards

The Food and Agriculture Organization (FAO) is an international organization focused on agricultural development. Established in 1945 by 44 member countries of the United Nations, FAO's specialists are involved in providing policy solutions, defining standards, setting international regulatory frameworks, and offering technical support across a wide range of topics related to agriculture and rural development. These areas include agricultural production, consumer protection, food security, forestry, environmental concerns, and more. FAO has established the standards for water composition used in agriculture in FAO Report number 29. These standards are widely regarded as the best quality parameters for water used in agricultural purposes. The report identifies ten water parameters with specified limits for agricultural use. Exceeding these limits is considered unacceptable. Table 2 presented the FAO report on permissible limits for agricultural water compositions.

2.2.3. Iranian Standards - Institute of Standards and Industrial Research

The Institute of Standards and Industrial Research of Iran has provided guidelines and standards for the quality of water used in pressurized irrigation systems including drip and sprinkler irrigation. These standards specify the permissible limits for key chemical parameters in water for these two irrigation systems. If the levels of these parameters exceed the allowed limits set by these standards, the water becomes unsuitable, potentially causing problems within the irrigation system or for the plants being irrigated.

2.2.4. Drip Irrigation

Clogging of drip emitters in drip irrigation systems is closely related to water quality, and chemical treatment and filtration of water are effective methods for preventing the risk of clogging pipes and emitters. The factors causing emitter clogging can be categorized into three main groups: physical, chemical, and biological (or microbial) factors. Physical factors include suspended materials such as sand, silt, clay, plastic materials, organic matter (such as animal and plant residues), and microbes (e.g., algae, diatoms, larvae, etc.). Chemical factors responsible for emitter clogging include calcium carbonate and ferric iron precipitation. Biological clogging occurs in water containing organic matter, hydrogen sulfide, and iron. The presence of hydrogen sulfide and iron in water with organic carbon leads to the formation of sludge strands along the walls of pipes, causing blockages. The use of chemical fertilizers and increased water temperature inside the pipes exacerbates this sludge formation (Alizadeh, 1997; Ramzanian Azizi et al., 2023). The Institute of Standards and Industrial Research of Iran has established a standard for the quality of water used in drip irrigation (Table 3).

2.2.5. Sprinkler Irrigation

In sprinkler irrigation, since water is sprayed onto the surface of the leaves, the levels of salinity, bicarbonate, sodium, and chloride in the irrigation water are of great significance. In sensitive plants, while sodium and chloride toxicity may not be a concern with surface irrigation, in sprinkler irrigation, due to foliar absorption, such issues may arise (Ayers & Westcot, 1985; Maroufpoor et al., 2018). The Institute of Standards and Industrial Research of Iran has established a standard for the quality of water used in sprinkler irrigation (Table 3).

2.2.6. Salinity Index

The potential salinity index is used to describe the quality of irrigation water for electrical conductivities higher than 250 microsiemens per centimeter (ds/m 0.25). Donin (1954) stated that the suitability of water for irrigation does not solely depend on the concentration of dissolved salts in the water, as salts with low solubility precipitate in the soil and their concentration increases with each irrigation. The rise in the concentration of salts with high solubility leads to an increase in soil salinity. The potential salinity index estimates the risk of salinity increase due to rising levels of chloride and sulfate. An increase in chloride and sulfate ions can elevate the osmotic potential of the soil solution when the available soil moisture is less than 50% (Delbari et al., 2016; Emamgholizadeh, 2008). The potential salinity index is calculated using Equation (1).

$$PS = \frac{SO_4}{2} + Cl \tag{1}$$

Based on the potential salinity index, water quality can be classified into three categories: good ($PS < 3$), medium ($3 \leq PS \leq 15$), and poor ($PS > 15$), measured in milliequivalents per liter.

The total ratio is another parameter used to assess the suitability of water for irrigation. This ratio compares sodium with calcium and magnesium. Waters with a total ratio less than one are considered suitable for irrigation. The total ratio is calculated using Equation (2).

$$KR = \frac{Na}{Ca + Mg} \tag{2}$$

The magnesium absorption ratio is also used to assess the risk of magnesium and is calculated using Equation (3), expressed as a percentage.

$$MAR = \frac{Mg}{Ca + Mg} \times 100 \tag{3}$$

If the magnesium absorption ratio exceeds 50 percent, magnesium is considered a risk factor. As groundwater levels decline, the water becomes not only more saline but also more bitter. The bitterness of the water is attributed to the presence of magnesium.

Table 2. Permissible Limits for Agricultural Water (FAO).

Parameter	Symbol	Permissible Range	Unit	Parameter	Symbol	Permissible Range	Unit
Bicarbonate	HCO3	0-10	meq/lit	Electrical conductivity	EC	0-3000	µmhos/cm
Chloride	Cl	0-30	meq/lit	Total dissolved solids	TDS	0-2000	mg/L
Sulfate	SO4	0-20	meq/lit	Calcium	Ca	0-20	meq/L
Sodium adsorption ratio	SAR	0-15	meq/lit	Magnesium	Mg	0-0.5	meq/L
pH	pH	5.6-8		Sodium	Na	0-40	meq/L

Table 3. Standards of the Iranian Institute of Standards and Industrial Research.

sprinkler irrigation				**Drip irrigation**			
Parameter	No limitation	Low to medium limitation	Severe limitation	**Parameter**	No limitation	Low to medium limitation	Severe limitation
Na (meq/L)	< 3	➢ 3		EC (µmhos/cm)	< 800	800-3000	➢ 3000
Cl (meq/L)	< 3	➢ 3		TDS (mg/L)	< 500	500-2000	➢ 2000
HCO3 (meq/L)	< 1.5	1.5-8.5	> 8.5	pH	< 7	7-8	➢ 8

2.2.7. Wilcox Classification

One of the most important methods for classifying irrigation water is the Wilcox classification. In this method, irrigation water is classified into 16 categories, from S1C1 to S4C4, based on Electrical Conductivity (EC), representing the salinity hazard, and the Sodium Adsorption Ratio (SAR), representing alkalinity. The symbol "C" indicates EC, and "S" indicates SAR. Table 4 shows the limits for EC and SAR in this classification. In the horizontal axis, the values of electrical conductivity are represented, and on the vertical axis, the sodium adsorption ratio is shown. The low salinity group (C1) is suitable for almost all types of soil for irrigation. The moderate salinity group (C2) can be used easily for salt-tolerant plants, but leaching is necessary for salt-sensitive plants. The high salinity group (C3) should not be used in soils with poor drainage, and if used continuously, regular leaching and plowing are required to prevent salinity issues. The very high salinity group (C4) can only be used in conditions where the soil has high permeability and proper drainage, leaching is performed effectively, and plants with very high salt tolerance are cultivated. The low-alkalinity group (S1) is suitable for any soil and plant, but it is preferable to use it for plants that are not sensitive to sodium. The moderate alkalinity group (S2) can be easily used in coarse-textured soils with high permeability.

However, in heavy-textured soils with high cation exchange capacity and under low leaching conditions; it may be difficult to use due to the higher sodium hazard. The high alkalinity group (S3) is generally suitable for sandy soils with high permeability and low overall salt concentration. It can also be used more easily in soils containing gypsum. The very high alkalinity group (S4) is not suitable for irrigation but can be used in soils with low salt concentration and higher levels of soluble calcium, provided that leaching is practiced and chemical amendments like gypsum are added.

In Figure 2, C1S1 represents excellent water, C1S2, C2S2, and C2S1 represent good water, C1S3, C2S3, C3S1, C3S2, and C3S3 represent moderate water, and C1S4, C2S4, C3S4, C4S4, C4S1, C4S2, and C4S3 represent unsuitable water for agriculture.

Table 4. EC and SAR limits in Wilcox classification.

EC			SAR		
Class	EC (ds/m)	Quality	**Class**	SAR (meq/lit) $^{0.5}$	Quality
C1	< 0.25	Excellent	S1	< 10	Excellent
C2	0.25-0.75	Good	S2	10-18	Good
C3	0.75-2.25	Moderate	S3	18-26	Moderate
C4	➢ 2.25	Poor	S4	➢ 26	Poor

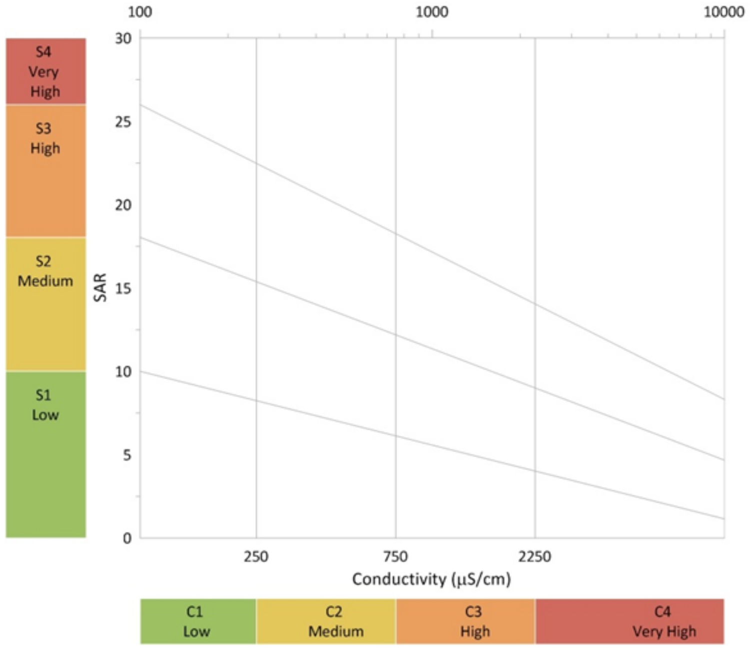


Figure 2. Wilcox classification diagram

3. Results and Discussions

3.1. FAO Standards

The FAO standard includes permissible limits for ten parameters: electrical conductivity, total dissolved solids (TDS), calcium, magnesium, sodium, bicarbonate, chloride, sulfate, Sodium Adsorption Ratio (SAR), and pH. The average values of these ten parameters in the Gonabad plain over the period from 2007 to 2022 were compared with the permissible limits specified by the FAO Standard, and the following results were obtained:

According to the Table 5, the average values of calcium, sodium, bicarbonate, chloride, sulfate, SAR, and pH in all years fell within the permissible limits set by the FAO. However, the total dissolved solids parameter exceeded the FAO limits in the years 2012-2013, 2016-2017, 2017-2018, 2018-2019, and 2019-2020, while in the remaining years, it was within the permissible range. The average values for electrical conductivity and magnesium also exceeded the FAO permissible limits in all years. The results suggest that the groundwater in Gonabad plain is not suitable for agricultural use based on the FAO standards, particularly due to the high levels of magnesium and electrical conductivity. For crops, herbs, and trees that are sensitive to these two parameters, this water should not be used. Increased magnesium concentration not only causes direct toxicity to plants but also leads to the degradation of soil structure. Soil degradation refers to the reduction or disruption of soil permeability, which can severely affect irrigation systems and agricultural productivity. Unfortunately, the risks associated with magnesium alkalinity are often overlooked. However, these risks are becoming more significant as groundwater levels continue to decline. Water with high salinity and electrical conductivity is also toxic to plants and poses a risk of soil salinization. High concentrations of salts in the soil create dry physiological conditions, which means that although the soil may appear moist, plants will wilt due to the roots’ inability to absorb water. This condition can have long-term negative effects on crop yields and soil health.

Table 5. Average values of irrigation water quality parameters in the Gonabad plain from 2007-2022.

Year	CA	MG	NA	SAR	EC	TDS	pH	HCO_3	CL	SO_4
	meq/lit	meq/lit	meq/lit	$(meq/lit)^{0.5}$	(µmhos/cm)	mg/lit	-	meq/lit	meq/lit	meq/lit
2007-2008	3.93	6.45	20.74	9.68	3154.94	1987.61	8.28	3.28	13.73	13.99
2009-2010	4.89	6.53	20.39	8.94	3147.13	1982.69	8.18	4.39	13.61	14.13
2011-2012	4.83	9.73	16.58	6.82	3082.44	1941.94	8.24	3.96	14.48	12.80
2012-2013	4.00	5.84	22.08	10.66	3200.19	2016.12	7.97	3.18	14.33	14.73
2013-2014	4.05	7.35	20.05	8.79	3159.13	1990.25	8.06	3.74	14.57	18.73
2015-2016	4.48	5.39	20.16	9.20	3023.08	1900.51	7.24	5.27	12.97	11.07
2016-2017	5.06	5.12	23.03	10.56	3261.33	2054.64	7.69	5.36	13.71	12.43
2017-2018	5.86	5.63	22.78	9.88	3316.81	2089.59	7.68	5.60	14.04	12.04
2018-2019	5.75	6.03	21.19	9.08	3194.44	2012.50	7.50	5.74	13.44	11.48
2019-2020	5.35	5.67	21.64	9.69	3182.19	2000.54	7.50	5.54	13.66	11.65
2021-2022	5.88	6.08	21.48	9.17	3130.04	1968.25	7.75	6.28	13.54	11.53

3.2. Iranian Standards Institute of Standards and Industrial Research

The groundwater quality of Gonabad plain was assessed for use in drip and sprinkler irrigation systems. For this purpose, the average values of the chemical parameters of the groundwater in the Gonabad plain were compared with the standards set by the Institute of Standards and Industrial Research of Iran for drip and sprinkler irrigation systems. The results are as follows:

3.2.1. Drip Irrigation

To assess the quality of groundwater in Gonabad plain for drip irrigation, the average values of three-chemical parameters, including total dissolved solids (TDS), electrical conductivity (EC), and pH were used over the period from 2007–2022. These values were compared with the water quality standards for drip irrigation set by the Institute of Standards and Industrial Research of Iran (Table 3), and the following results were obtained: According to Table 6, the electrical conductivity parameter in all years falls within the severe limitation range. The Total Dissolved Solids (TDSs) parameter falls within the severe limitation range for the years 2012-2013, 2016-2017, 2017-2018, 2018-2019, and 2019-2020, while in the remaining years, it falls within the low to moderate limitation range. The pH parameter in the years 2007-2008, 2009-2010, 2011-2012, and 2013-2014 falls within the severe limitation range, while in the remaining years, it falls within the low to moderate limitation range.

3.2.2. Sprinkler Irrigation

To assess the quality of groundwater in Gonabad plain for sprinkler irrigation, the average values of three chemical parameters, including sodium, chloride, and bicarbonate were used over the period from 2007–2022. These values were compared with the water quality standards for sprinkler irrigation set by the Institute of Standards and Industrial Research of Iran (Table 3), and the following results were obtained: According to Table 6, the average values of sodium, chloride, and bicarbonate parameters in all years fall within the limitation range.

3.3. Irrigation Indices Ps, KR, and MAR

To assess the quality of groundwater in the Gonabad plain using irrigation indices, the values of irrigation indices from wells in Pasdaran, Alipour, Taghavi, Al-Mahdi, Abdolali, Ansari, Arjmand, Pourebrahim, Alizadeh, Jaddeh Sento, Ahmad Amin, Heidarzadeh, Jaddeh Kakhak, Yaghoubi, Mousa Zadeh, and Ghorban Beigi were determined over a 15-years period (Table 6).

The values of these indices in the Gonabad plain were compared with their permissible limits, and the following results were obtained. Based on Table 6, the average values of parameters such as Magnesium Absorption Ratio (MAR), Total Ratio (TR), and potential salinity (Ps) in all years (except for magnesium absorption ratio in 2017-2018 were found to fall into the unsuitable range. This indicates that the groundwater in Gonabad plain has a magnesium hazard; a high sodium-to-total calcium and magnesium ratio, and salinity resulting from chloride and sulfate parameters. Therefore, it is deemed unsuitable for agricultural uses, especially concerning the mentioned parameters.

Table 6. Standard Values and Irrigation Indices in Gonabad plain.

Year	**MAR**	**KR**	**Ps**	**CL**	**HCO3**	**NA**	**PH**	**TDS**	**EC**
	(%)	(ratio)	(meq/lit)	meq/lit	meq/lit	meq/lit	_	meq/lit	µmhos/cm
2007-2008	62.17	2	20.72	13.73	3.28	20.74	8.28	1987.61	3154.94
2009-2010	57.17	1.79	20.67	13.61	4.39	20.39	8.18	1982.69	3147.13
2011-2012	66.82	1.14	20.88	14.48	3.96	16.58	8.24	1941.94	3082.44
2012-2013	59.34	2.24	21.7	14.33	3.18	22.08	7.97	2016.12	3200.19
2013-2014	64.48	1.76	23.93	14.57	3.74	20.05	8.06	1990.25	3159.13
2015-2016	54.59	2.04	18.51	12.97	5.27	20.16	7.24	1900.51	3023.08
2016-2017	50.29	2.26	19.93	13.71	5.36	23.03	7.69	2054.64	3261.33
2017-2018	48.97	1.98	20.06	14.04	5.6	22.78	7.68	2089.59	3316.81
2018-2019	51.17	1.8	19.18	13.44	5.74	21.19	7.5	2012.5	3194.44
2019-2020	51.45	1.96	19.48	13.66	5.54	21.64	7.5	2000.54	3182.19
2021-2022	50.81	1.8	19.31	13.54	6.28	21.48	7.75	1968.25	3130.04

3.4. Wilcox Classification

The Wilcox classification was applied to assess the quality of water from 16 wells in the Gonabad plain over the period from 1386 to 2007 to 2022. The results are presented in Tables 7 and 8 (Data for the years 2010-2011, 1393 2014-2015, and some wells were unavailable).

According to the Wilcox classification, the results are as follows: The water quality of the wells in Ansari, Pourebrahim, Ahmad Amin, Jaddeh Kakhak, and Yaqoubi, in the years under review, falls into the "moderate" category for agricultural use (C3S1- C3S2- C3S3). However, the water from all other wells falls into the "unsuitable" category (C4S1-C4S2-C4S3-C4S4). These findings indicate that the majority of the groundwater in the Gonabad plain is not suitable for agricultural use, with only a few wells providing water of moderate quality for irrigation purposes.

Table 7. Wilcox classification of Groundwater Quality in Gonabad plain wells.

Well Name	**(2007-2008)**	**(2008-2009)**	**(2009-2010)**	**(2011-2012)**	**(2012-2013)**	**(2013-2014)**	**(2015-2016)**
Pasdaran	C4-S4	C4-S1	C4-S4	C4-S3	C4-S1	C4-S3	C4-S4
Alipour	C4-S2	C4-S1	C4-S2	C4-S2	C4-S1	C4-S2	C4-S2
Taghavi	C4-S3	-	C4-S3	C4-S2	C4-S1	C4-S3	C4-S3
Al-Mahdi	C4-S3	-	C4-S3	C4-S3	C4-S1	C4-S3	C4-S3
Abdolali	C4-S3	C4-S1	C4-S3	C4-S2	C4-S1	C4-S3	C4-S3
Ansari	C3-S2	-	C3-S2	C3-S2	C3-S1	C3-S2	C3-S2
Arjmand	C4-S3	-	C4-S3	C4-S3	C4-S2	C4-S3	C4-S4
Pourebrahim	C3-S2	C3S1	C3-S2	C3-S1	C3-S1	C3-S2	C3-S2
Alizadeh	C4-S4	C4-S1	C4-S3	C4-S4	C4-S1	C4-S4	C4-S4
Jaddeh Sento	C4-S4	-	C4-S4	C4-S2	C4-S2	C4-S4	C4-S4
Ahmad Amin	C3-S3	C3-S1	C3-S2	C3-S2	C3-S1	C3-S3	C3-S3
Heidarzadeh	C4-S3	C4-S2	C4-S3	C4-S2	C4-S2	C4-S3	C4-S3
Jaddeh Kakhak	C3-S2	-	C3-S2	C3-S1	C3-S2	C3-S2	C3-S2
Yaqoubi	C3-S2	C3-S2	C3-S2	C3-S2	C3-S2	C3-S2	C3-S2
Mousavi Zadeh	C4-S3	-	C4-S3	C4-S3	C4-S2	C4-S3	C4-S2
Ghorban Beigi	C4-S3	-	C4-S3	C4-S1	C4-S2	C4-S3	C4-S3

Table 8. Wilcox Classification of Groundwater Quality in Gonabad plain wells.

Well Name	(2016-2017)	(2017-2018)	(2018-2019)	(2019-2020)	(2020-2021)	(2021-2022)
Pasdaran	C4-S1	C4-S4	C4-S1	C4-S3	C4-S1	C4-S4
Alipour	C4-S1	C4-S2	C4-S1	C4-S2	C4-S1	C4-S2
Taghavi	C4-S1	C4-S3	C4-S1	C4-S3	-	C4-S3
Al-Mahdi	-	C4-S3	C4-S1	C4-S3	C4-S1	C4-S3
Abdolali	C4-S1	C4-S3	C4-S1	C4-S3	-	C4-S3
Ansari	C3-S1	C3-S2	C3-S1	C3-S2	-	C3-S2
Arjmand	C4-S2	C4-S4	C4-S2	C4-S4	-	C4-S4
Pourebrahim	C3-S1	C3-S2	C3-S1	C3-S2	-	C3-S2
Alizadeh	C4-S1	C4-S4	C4-S2	C4-S4	C4-S2	C4-S4
Jaddeh Sento	C4-S2	C4-S4	C4-S2	C4-S4	-	C4-S4
Ahmad Amin	C3-S1	C3-S3	C3-S1	C3-S3	C3-S2	C3-S3
Heidarzadeh	C4-S2	C4-S3	C4-S2	C4-S3	-	C4-S3
Jaddeh Kakhak	C3-S2	C3-S3	C3-S2	C3-S3	-	C3-S3
Yaqoubi	C3-S2	C3-S2	C3-S2	C3-S2	C3-S2	C3-S2
Mousavi Zadeh	C4-S2	C4-S2	C4-S2	C4-S2	-	C4-S2
Ghorban Beigi	C4-S2	C4-S3	C4-S2	C4-S3	-	C4-S3

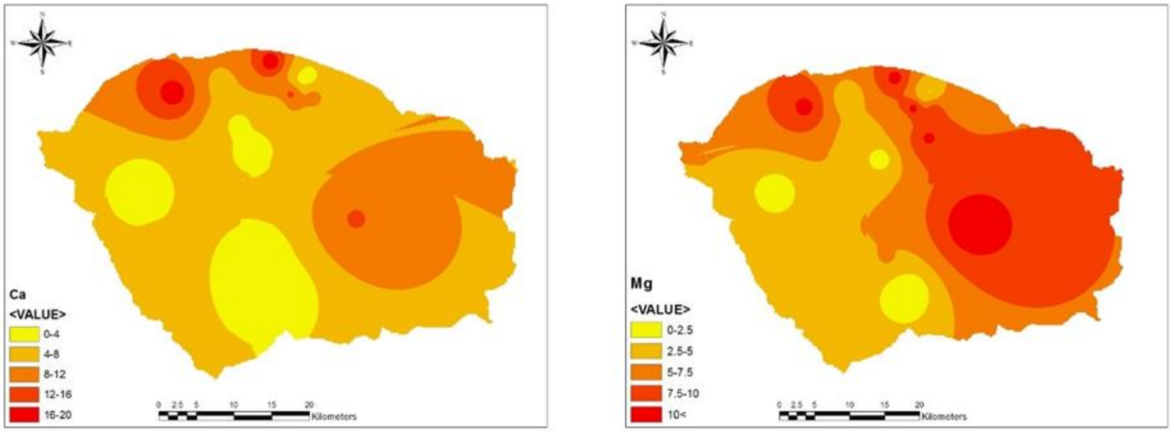
3.5. Maps of Parameter and Index Zoning

To better understand the spatial distribution of the chemical parameters of water and the calculated indices in the Gonabad plain, zoning maps were created using the IDW method in GIS software (Figures 3).

The water quality status of the Gonabad plain, in terms of various chemical parameters, has been evaluated across different diagrams (Figures 3(a) to 3(n)). The calcium concentration throughout the plain is below 20, which is considered suitable according to FAO standards (Figure 3(a)). However, the magnesium concentration in the eastern half and some northern regions exceeds 5, which is deemed unsuitable based on FAO guidelines (Figure 3(b)). Similarly, sodium concentration in the eastern and northern sections of the plain exceeds 40, which is considered unsuitable (Figure 3(c)). Furthermore, in the case of sprinkler irrigation, sodium levels are higher than 3 in nearly the entire plain, representation it unsuitable for this type of irrigation. Chloride concentrations in the eastern and northern areas exceed 30 (Figure 3(d)), which are also considered unsuitable based on FAO standards. In sprinkler irrigation, chloride concentrations across most of the plain are above 3, thus also unsuitable. In contrast, bicarbonate levels across the entire Gonabad plain are below 10, which is considered suitable according to FAO standards (Figure 3(e)). In sprinkler irrigation, bicarbonate levels range from 1.5 to 8.5 across most of the plain, falling within the low to moderate limitation category. Electrical conductivity in parts of the central and southwestern regions of the plain is below 3000 µS/cm, which is considered suitable (Figure 3(f)). In drip irrigation, electrical conductivity in these areas ranges from 800 to 3000 µS/cm, placing it within the low to moderate limitation category. The Total Dissolved solids (TDSs) in parts of the central and southwestern plain, as well as a small portion of the northern plain, are below 2000, which is considered suitable (Figure 3(g)). For drip irrigation, TDS in these regions ranges from 500 to 2000, which falls within the low to moderate limitation category. The pH levels across the entire plain, except for a small portion in the south, range from 6.5 to 8, which is considered suitable according to FAO standards (Figure 3(h)). In drip irrigation, the pH in these areas ranges from 7 to 8, also placing it within the low to moderate limitation category. The Sodium Absorption Ratio (SAR) is less than 15 throughout the plain, except for certain regions in the north and south, which is considered suitable according to FAO standards (Figure 3(i)). Sulfate concentrations exceed 20 in small areas in the north and parts of the central plain, especially toward the east, which is considered unsuitable (Figure 3(j)). The potential salinity index is concentrated in the eastern and northern parts of the plain, where it exceeds 15, indicating high salinity levels due to sulfate and chloride. This makes the water unsuitable for irrigation in these areas (Figure 3(k)). In disparity, in the western and southwestern regions, the index is below 3, which is considered suitable, while other areas fall within the 3 to 15 range, which is classified as having moderate limitations. The total ratio index in the eastern, northern, and central regions of the plain exceeds 1, indicating that sodium content is higher than the combined magnesium and calcium content, making it unsuitable for irrigation (Figure 3(l)). In the western and southwestern regions, this index is less than 1, which is considered suitable. Finally, the distribution of the Wilcox index for the Gonabad Plain suggests that water quality is unsuitable for agricultural use in the eastern and northern regions, which exhibit the highest concentrations of chemical parameters (Figure 3(n)). Conversely, the central, southern, and western areas, which include locations of several Qanats and springs, fall within the good to moderate range for water quality.

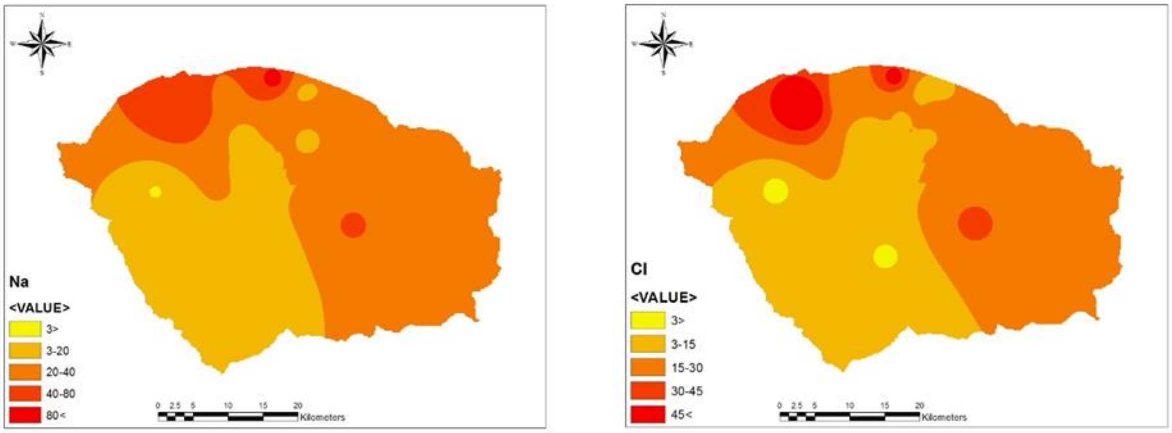
Similar findings have been reported by Salari, who investigated the groundwater quality of the Shiraz plain using water quality indices for agricultural, drinking, and industrial purposes. The results obtained from the Wilcox and Schuler quality indices indicated that the groundwater was of moderate quality for agricultural use and acceptable for drinking purposes (Salari, 2024). Likewise, Motamedi Rad et al. (2021) evaluated the quality of karst aquifer water resources in Rooyin, Esfarayen, located in the North Khorasan Province. Their findings, based on the Wilcox index, revealed that 15% of the springs contained saline water but were still usable for agriculture, while the remaining springs were classified as suitable for agricultural purposes (Motamedi Rad et al., 2021). In contrast, the findings of the present study indicate that the majority of the groundwater in the Gonabad plain is not suitable for agricultural use, with only a few wells providing water of moderate quality for irrigation purposes. This highlights the regional variations in groundwater quality and underscores the need for localized water resource management strategies.

(a) (b)



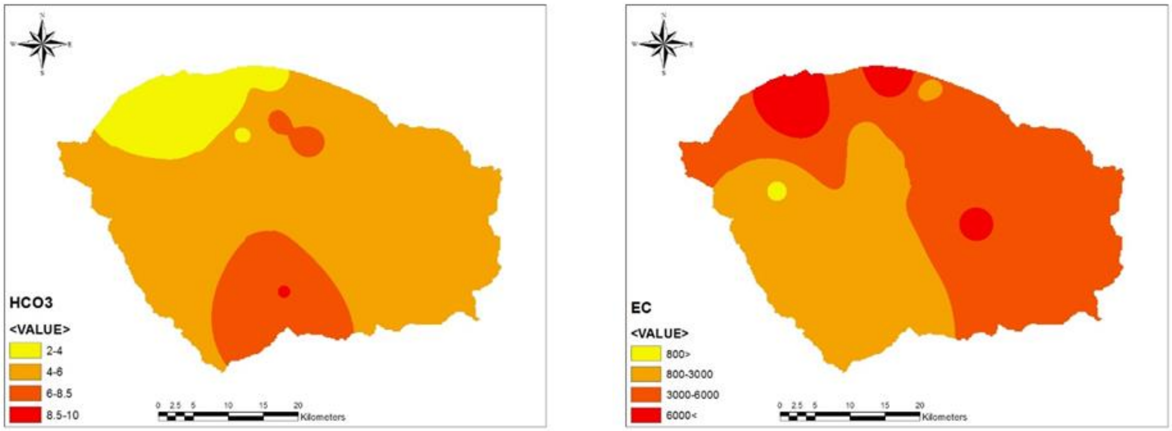
Calcium Zoning in 2021-2022 Magnesium Zoning in 2021-2022

(c) (d)



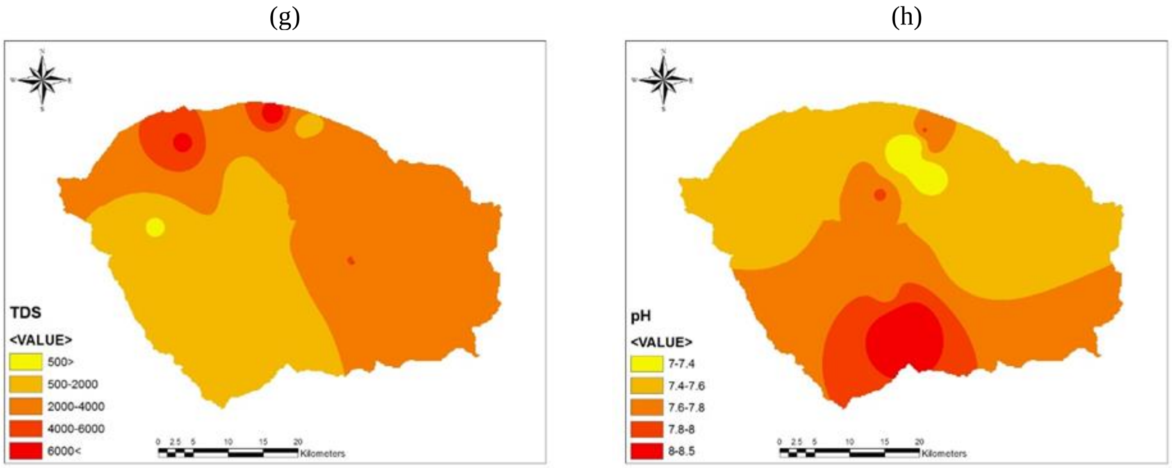
Sodium Distribution Map in 2021-2022 Chloride Distribution Map in 2021-2022

(e) (f)



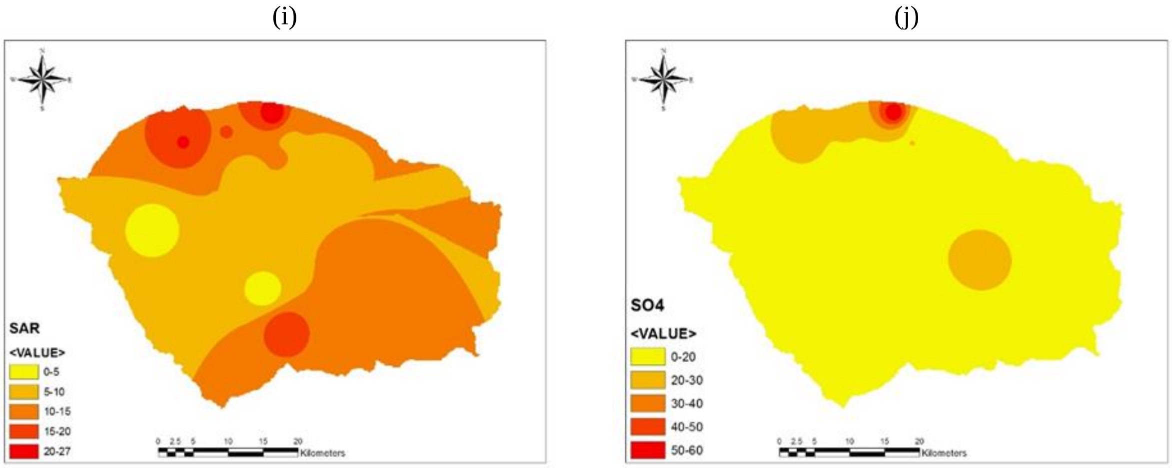
Bicarbonate Distribution Map in 2021-2022 Electrical Conductivity (EC) Distribution Map in 2021-2022

Figure 3. Spatial distribution of water chemical parameters and the calculated indices in the Gonabad plain.



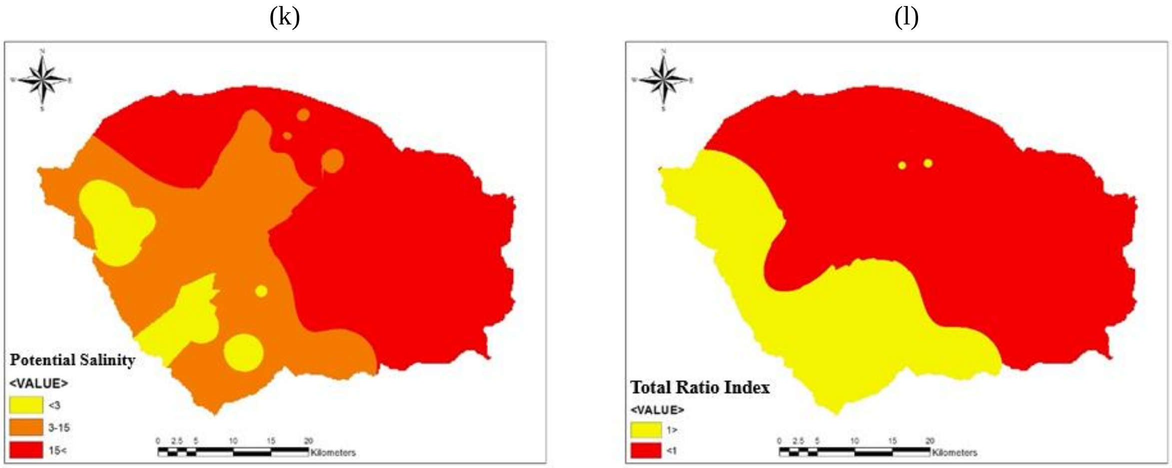
Total Dissolved Solids (TDS) Distribution Map in 2021-2022

pH Distribution Map in 2021-2022



Sodium Absorption Ratio (SAR) Distribution Map in 2021-2022

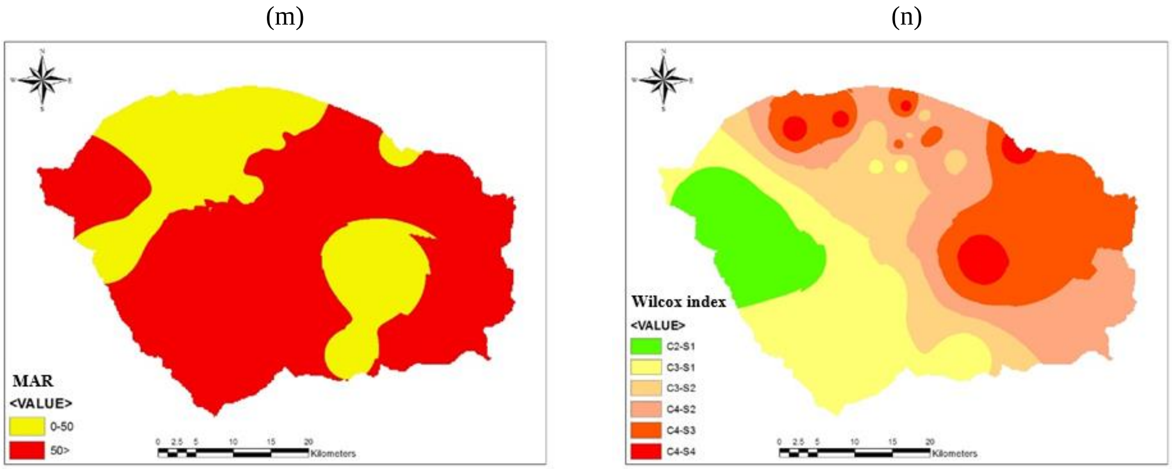
Sulfate Distribution Map in 2021-2022



Potential Salinity Index Distribution Map in 2021-2022

Total Ratio Index Distribution Map in 2021-2022

Figure 3. (Contined)



MAR Index Distribution Map in 2021-2022 Wilcox Index Distribution Map in 2021-2022

Figure 3. (Contined)

4. Conclusions

In this research work, the concentrations of calcium, magnesium, sodium, electrical conductivity, total dissolved solids, sodium adsorption ratio, pH, bicarbonate, chloride, and sulfate from 2007 to 2022 were compared with FAO standards in the Gonabad plain. a key innovation of this research work lies in its comprehensive water quality assessment, which integrates both international and national standards (Institute of Standards and Industrial Research of Iran). This approach allows for a better understanding of the suitability of water quality for agricultural applications at both the local and global levels. The results revealed that two parameters, electrical conductivity and magnesium, exceeded their permissible limits. During this period, total dissolved solids and pH were categorized within the low to moderate limitation range for drip irrigation, while electrical conductivity cut down within the severe limitation range. In disparity, the parameters of sodium, chloride, and bicarbonate were classified as low to moderate limitations for sprinkler irrigation. According to the Wilcox classification, the water quality from the wells of Ansari, Pourebrahim, Ahmad Amin, Jaddeh Kakhak, and Yaqoubi during 1386-2007-2022 was deemed to be of moderate quality for agricultural use, while the remaining wells were categorized as unsuitable, and required corrective measures. Additionally, three indices-potential salinity, total ratio, and magnesium adsorption ratio were found to be in the unsuitable range in the Gonabad plain. This research encountered a significant limitation due to the unavailability of complete data for certain years and discrete time periods. The absence of data pertaining to water quality parameters in some years, attributable to deficiencies in record keeping and inconsistent sampling protocols, presented a particular obstacle. This data constraint impeded a comprehensive analysis of temporal trends in water quality. Consequently, the establishment of robust and integrated monitoring systems is imperative to ensure data integrity and completeness in future investigations. Improving water quality in the Gonabad plain requires a multi-faceted approach. Prioritizing strict limits on water extraction in areas with low or critical water quality is crucial to alleviate pressure on these resources, and prevent further salinity and contamination. Optimal water management should also include stricter monitoring of unauthorized withdrawals and specific restrictions on groundwater use. Additionally, educating farmers on salt-tolerant crops and appropriate agricultural practices can maintain productivity, while mitigating the negative effects of salinity. This integrated strategy will ultimately enhance both agricultural productivity and long-term water quality. Future research endeavors should address two key priorities. Firstly, investigations into innovative groundwater treatment methodologies, with a particular emphasis on high-salinity regions such as the Gonabad plain, are justified to identify and develop efficacious solutions for enhancing water quality in agricultural contexts. Secondly, the development of predictive water quality models incorporating machine learning algorithms and simulating the effects of both management interventions and climate change scenarios should be pursued. Such models will facilitate more accurate projections of future water quality dynamics, thereby enabling more informed and practical water resource management strategies.

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Conflicts of Interest

The author declares no conflict of interest.

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