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Iran’s Groundwater Hydrochemistry
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Abstract Iran's groundwater hydrochemistry has not been well understood. In this study, Iran's groundwater hydrochemistry is evaluated using a rich, ground-trusted data sampled from 9,468 wells distributed across the country in 2011. Twelve groundwater quality parameters were analyzed in each sample, resulting in 113,616 parameters over the study period. Examination of anions-cations shows that concentrations of sodium, calcium, chloride, and sulphate are higher than the acceptable threshold for drinking-use suggested by the World Health Organization in about 40%, 21%, 25%, and 20% of the samples, respectively. The results of the water quality index reveal that most of the groundwater resources in the central, southern and eastern regions of Iran, which supply the majority of the domestic water for populated cities, do not meet the requirements for drinking-use. Although the groundwater in northern parts fulfills the requirements for irrigation-use, it is only suitable for irrigation of salinity-friendly crops in central, eastern and southern regions. Ionic types and hydrochemistry facies indicate the dominance of mix water type in 13 out of 30 of Iran's sub-basins, followed by sodium-chloride water type in nine sub-basins. Local geology and lithology are mainly attributed to the distribution of groundwater facies in Iran. In general, our findings reveal a distinctive relationship between Iran's geological-geomorphological features and hydrochemical facies/groundwater quality. The findings can be used in the formulation of new strategies and policies for Iran's groundwater quality management in the future.

1. Introduction
Iran is known as a hotspot with respect to groundwater depletion in the world (Dalin et al., 2017; Döll et al., 2014). Easy access, reliability, inexpensive energy, and insufficient supervision have resulted in a growing number of authorized and unauthorized groundwater extraction points, leading to national worries over the consequences for water quality (Mirzavand & Bagheri, 2020; Nasrabadib & Maedeh, 2014; Rezaei et al., 2020). Noori et al. (2021) concluded that the number of groundwater extraction nodes (e.g., wells, qanats and springs) increased from about 546,000 to over a million only during a 14-year period starting from 2002. Also, according to the official reports issued by the Iranian Parliament Research Center (IPRC, 2017), about 5 km² out of the 50 km² of groundwater extracted annually comes from non-renewable groundwater sources. Such over extractions have led to:

1. An alarming pressure on Iran's groundwater resources (IGWR), causing a severe and widespread decline in water levels across the country of about 50 cm yr⁻¹ during the last two decades (Noori et al., 2021)
2. Socio-physical crises such as population displacement (Danaei et al., 2019; Madani et al., 2016; Panahi et al., 2020) and unprecedented/extensive land subsidence (Motagh et al., 2008)
3. Fundamental environmental challenges such as saltwater intrusion and groundwater quality deterioration (Ebrahimi et al., 2016; Kardan Moghaddam et al., 2017; Madani et al., 2016; Motevalli et al., 2018; Noori, Ghahremanzadeh et al., 2019; Vesali Naseh et al., 2018)

A safe water supply to meet water needs for Iran's growing population and expanding agriculture is directly connected to groundwater quality. Therefore, understanding Iran's groundwater quality and its suitability for different usages is beneficial for the country's sustainable water resources management. It is important in a country such as Iran where groundwater supplies more than 55% of the national’s water demand, which its contribution increases to even more than 80% in rural communities (IPRC, 2017). However, scientific
investigations into Iran’s groundwater quality assessment are usually local and have limited coverage (Amiri et al., 2014; Barzegar et al., 2019; Chitsazan et al., 2017; Ghahremanzadeh et al., 2018; Mirzavand et al., 2020; Moghaddam & Fijani, 2008; Nadiri et al., 2013; Noori et al., 2020; Rezaei and Hassani, 2018; Sheikhi et al., 2020). There is no a countrywide, large-scale analysis to show Iran's groundwater suitability for drinking and irrigation uses although a rich record of studies can be found associated with the decline in groundwater storage, discharge, level, and withdrawal as well as groundwater extraction points (Forootan et al., 2014; Joodaki et al., 2014; Khaki et al., 2018; Nabavi, 2018; Noori et al., 2021; Panahi et al., 2020).

Meanwhile, the reliance on groundwater, as a clean source of water, has been rapidly increasing in different parts of the country as a result of the severe decline in surface water availability. This resulted in elevated groundwater salinity in almost all regions of Iran (IPRC, 2017; Noori et al., 2021). Given the importance of groundwater quality in Iran, this study aims to fill the gaps in knowledge of the hydrochemical composition of IGWR in different regions of the country. In this regard, Iran's groundwater suitability for drinking and irrigation uses and dominant hydrochemical facies are investigated with a rich, ground-trusted database across the country. In general, the output of this study shows the basic requirements for Iran's groundwater quality adaptation process while considering water requirements for different purposes.

2. Materials and Methods

2.1. Study Area

Iran, a country in southwestern Asia (45°–65° East longitude and 25°–45° North latitude), has an area of about 1,648,000 square kilometers (km²). The most important topographical features of this country are the Zagros and Alborz mountain chains in the north, west and center, which affect the climate and population distribution across Iran (Masih et al., 2011). With a population of more than 79 million (in 2015), Iran is one of the most populous country in the Middle East (Mehri et al., 2020). Iran is one of the few countries in the world to experience four distinct seasons at a same time. The mean annual rainfall of the country is about 241 mm, with conspicuous spatiotemporal diversity and variability (Tabari & Talaee, 2011). The annual average temperature in Iran varies from less than 6°C in the northwest to more than 28°C in the southeast (Araghi et al., 2015).

Iran’s geological structure can be divided into six territories:

1. The Arvand-roud plain, made of Paleozoic/Mesozoic Tertiary sediment. This plain is enveloped by early alluvial deposits
2. The bended belt of Zagros, consisting of a chain of carbonate-based sedimentary rocks from the initial Mesozoic to the end of the Tertiary age
3. The Zagros thrust plain, which borders Zagros Mountain to the eastern parts of Iran
4. The Central Plateau, which is a complex plain dominated by granitic intrusions, volcanic activity, and metamorphism
5. Alborz Mountain, built mainly of marine sedimentary rocks from the Paleozoic, Cretaceous and Mesozoic age and volcanic rocks from the Tertiary age
6. The Lut plain, a “Median Mass” feature with no effect from tectonic movements (Issar, 1969; Stoecklin, 1968)

With respect to the increasing demand for water as well as a decrease in surface water availability, the Iran Water Resources Management Company (IWRMC) has paid special attention to the use of semi-deep wells (IWRMC, 2020) in order to increase the safe water supply's reliability and consistency by increasing the number of withdrawal points (Noori et al., 2021). Because of this, from 1970 to 2014, the number of wells has increased by more than 16.7 times, leading to an increase in groundwater consumption from about 18 km³ in the 1970s to more than 79 km³ in 2006 (Nabavi, 2018). Agriculture accounts for about 11% of Iran's net gross domestic product (Emadodin et al., 2012). With an agricultural area of about 16 million hectares (Maghrebi et al., 2020), Iran produces about 128 million tons of crops annually. Groundwater resources provide about 90% of the agricultural sector’s water needs. In many parts of the country (e.g., the center, east, and southeast), groundwater is the only available source of water for drinking and irrigation uses (Maghrebi et al., 2020).
2.2. Data Analysis

In this study, we used groundwater quality data sampled from 9,468 observation wells distributed across Iran in 2011 (Figure 1A). We used the database sampled in 2011 since this year included the richness and most reliable groundwater quality data that properly distributed across the country. Groundwater quality data included major cations (i.e., Ca^{2+}, Mg^{2+}, Na^+ and K^+), major anions (i.e., HCO_3^−, SO_4^{2−}, Cl^− and CO_3^{2−}), pH, electrical conductivity (EC), total dissolved solids (TDS) and total hardness (TH).

We simply managed the groundwater quality data measured at sampling points to picture out the groundwater hydrochemistry and its suitability for different usages across Iran. The data were monitored seasonally, biannually, or annually. First, the data measured were clustered as cations, ions and state variables such as pH, EC, TDS and TH using Excel Software with Pivot Table Tools. Then, annual mean values of all groundwater quality data measured at each sampling point were used for further analyses. The suitability of groundwater resources for drinking-use has been assessed by: (a) a comparison of the physiochemical characteristics of water samples as well as state variables with permissible values recommended by the World Health Organization (WHO, 1993), and (b) the drinking water quality index (WQI) introduced by Tarawneh et al. (2019). WQI, as a general tool, gives a good insight into water suitability in terms of water quality assessment (Noori, Berndtsson, et al., 2019). Also, evaluation of groundwater for irrigation-use was carried out with respect to the guidelines suggested by the U. S. Salinity Laboratory diagram (USSL, 1954), and a calculation of several indices, such as sodium absorption rate (SAR) (Richards, 1954), sodium percentage (Na%) (Wilcox, 1955), magnesium hazard (MH) (Szabolcs, 1964) and Kelly’s ratio (KR) (Kelley, 1963). Piper diagram (Piper, 1944) was used to determine the dominant water types in Iran’s sub-basins. Piper diagram supposes that (a) Ca^{2+} and Mg^{2+} (as alkaline earths) and Na^+ (alkali metal) are the most common cations, and (b) HCO_3^− (as a weak acid) and SO_4^{2−} and Cl^− (as strong acids) are the most abundant anions. Detailed information on Piper diagram and the corresponding different water types is given in Figure S1.

To spatially investigate the groundwater quality with respect to drinking and irrigation uses, the deterministic inverse distance weighting (IDW) interpolation method was used. This interpolation method has been well evaluated in groundwater studies (Gong et al., 2014; Ilayaraja & Ambica, 2015; Nistor et al., 2020). Detailed information on the methodology used in this study is shown in Figure S2.

2.3. Data Quality Control/Assurance

All analyses and results presented here heavily rely on the quality of measured groundwater data. In this study, all groundwater quality data used were sampled and analyzed under supervision of the IWRMC. This government organization performs various types of quality control/assurance to ensure the groundwater quality data can be trusted for water resources management activities. In this regard, groundwater quality data is measured in trusted water and wastewater laboratories licensed by the Iran Department of Environment, according to the standard methods suggested by the American Public Health Association (APHA, 2005). Then, the raw data is made publicly available via the Data Archive of the IWRMC (http://wrs.wrm.ir/amar/login.asp). Duplicates are usually performed for randomly chosen laboratory tests before the data is released and added to the website. To boost confidence in the data, we reevaluated the accuracy of the chemical analyses using an ion charge balance approach with an acceptable limit of ±10%, as suggested by Freeze and Cherry (1979). This is a fundamental approach to ensure the quality control of ions analyses of water samples (Fritz, 1994). In addition, our investigation indicated that the measured EC data were strongly correlated with the corresponding TDS, boosting confidence in the groundwater quality data. Detailed information on the different sources of uncertainty as well as quality control/assurance procedures on the Iran’s groundwater data is given by Noori et al. (2021).

3. Results

3.1. Drinking-Use Suitability

Cations, anions, pH, EC, TDS and TH were analyzed to determine groundwater suitability for drinking-use. The minimum, maximum, and mean (standard deviation) concentrations of Na^+ were about 0, 9,867 and 324 (±554) mg/L across Iran. Sodium concentration was above the permissible limit for drinking-use (i.e.,
Figure 1. (A) Spatial distribution of 9,468 observation wells used in this study, and (B) drinking water quality index calculated for each observation wells across Iran.
200 mg/L (WHO, 1993)), in about 40% of the samples, mainly located in the east, south, and center of Iran (Figure 2A). High concentrations of this cation in water can cause high blood pressure or pose a risk to people suffering from kidney, circulatory or heart diseases (Kumar et al., 2019). The minimum, maximum and mean (standard deviation) concentrations of K⁺ were about 0, 532 and 5 (±20) mg/L, respectively. A small percentage of samples (0.2%) showed concentrations over 200 mg/L, the permissible limit of K⁺ recommended by WHO (WHO, 1993). Although no concern was observed in the IGWR regarding high concentrations of K⁺ in almost all of the samples, most areas showed very low K⁺ level, so the concentration averaged across the county was only about 5 mg/L. High blood pressure, blood lipids, or lower catecholamine levels can be caused by a K⁺ deficiency in drinking water (WHO, 1993). The minimum, maximum and mean (standard deviation) concentrations of Mg²⁺ were about 0, 1,932 and 73 (±97) mg/L. These values for Ca²⁺ were about 0, 2,705 and 147 (±18) mg/L. About 0.77% and 21% of the samples showed concentrations above the permissible level of Mg²⁺ and Ca²⁺ in drinking water, 501 mg/L and 200 mg/L, respectively (Figure 2A) (WHO, 1993). In general, Ca and Mg as alkaline earth metals are commonly found in groundwater due to their abundance and solubility. Although the specific levels of these elements are essential for proper human bone growth, their high concentration can also cause significant hardness and water inefficiency (Vasyukov et al., 2019).

The minimum, maximum and mean (standard deviation) concentrations of Cl⁻ were about 0, 17,371 and 577 (±1,093) mg/L. The chloride level, as an indicator of groundwater pollution (Loizidou & Kapetanios, 1993), was above the desired concentration for drinking (600 mg/L [WHO, 1993]), in about 25% of the samples (Figure 2A). Higher concentrations of Cl⁻ in drinking water cause a salty taste and have a laxative effect on people who are not used to it (Bhardwaj & Singh, 2011; Bostanmaneshrad et al., 2018). The minimum, maximum and mean (standard deviation) levels of SO₄²⁻ were about 0, 12,584 and 946 (±633) mg/L. In about 20% of the samples, SO₄²⁻ level was above the desired concentration for drinking-use (600 mg/L [WHO, 1993]). Dehydration and irritation of the gastrointestinal tract in human are concerns associated with high level of SO₄²⁻ in drinking water. Concentrations of HCO₃⁻ and CO₃²⁻ in the IGWR varied from 0 to 1,913 mg/L and 0 to 114 mg/L with a mean (standard deviation) level of about 259 (±144) and 6.6 (±3) mg/L, respectively. All examined samples lay within the desirable limit of CO₃²⁻ concentration (300 mg/L [WHO, 1993]), although 27% of the samples showed higher concentration of HCO₃⁻ than the permissible level suggested by WHO for drinking-use (300 mg/L, Figure 2A [WHO, 1993]). The health effects of CO₃²⁻ and HCO₃⁻ on the human body are unknown (Adimalla & Venkatayogi, 2018).

Figure 2B shows spatial distribution of pH in Iran that varies from 5.9 to 8.8 with a mean level (standard deviation) of about 7.7 (±0.36), indicating the overall alkaline nature of the IGWR. With respect to pH, about 99.85% of Iran has suitable drinking water, with unsuitable drinking water being mainly located in the Lake Urmia sub-basin. The permissible range of pH for drinking-use varies from 6.5 to 8.5 (WHO, 1993). Based on the spatial distribution of EC, groundwater resources in only about 20.2% of Iran's territory is allowable for drinking-use, that is, EC < 1,000 µS/cm (Meride & Ayenew, 2016), mainly located in north and west parts. The maximum, minimum and mean (standard deviation) values of TDS are about 32,695, 101 and 1,627 (±2,134) mg/L, respectively. With respect to TDS, groundwater resources in around 14% and 15% of Iran's land, respectively, are classified as desirable (TDS < 500 mg/L) and permissible (500 mg/L < TDS < 1,000 mg/L) for drinking-use (WHO, 1993). Others (around 71% of the country’s area), mainly located in eastern, southern and central parts, do not meet the required TDS level for drinking-use. Also, groundwater resources in about 50% of Iranian territories are not suitable, with respect to TH, for drinking-use, that is, TH > 500 mg/L (Meride & Ayenew, 2016). This groundwater is mainly located in southwestern, central, and eastern areas of the country (Figure 2B).

Groundwater quality was classified as excellent (WQI < 50), good (50 < WQI < 100), poor (100 < WQI < 200), very poor (200 < WQI < 300), and unsuitable (WQI < 300) in about 49% 24%, 17%, 6%, and 4% of observation wells, respectively (Figure 1B). According to WQI results, groundwater resources in most parts of the Lake Urmia sub-basin, and the center, east and the northern shores of the Persian Gulf are not suitable for drinking-use. Important populated cities such as Bandar-e Abbas, Isfahan, and Qom are located in these arid regions. Groundwater sources in these areas require some degree of treatment to be suitable for drinking-use. On the other hand, in the foothills of the Zagros and Alborz Mountains, where important populated cities are located, most of the wells are of good quality for drinking-use (Figure 1B).
Figure 2. (A) Spatial distribution of major cations and anions based on the threshold levels determined by World Health Organization for drinking-use, and (B) spatial distribution of pH, electrical conductivity, total dissolved solids and total hardness across Iran.
3.2. Irrigation-Use Suitability

Irrigation water quality, in terms of dissolved salts and alkalis, influences crop yield, as well as the physicochemical and biological features of agricultural soil. Based on the USSL diagram (USSL, 1954), water quality suitability for irrigation-use is classified as excellent (EC ≤ 250 µS/cm), good (250 < EC < 750 µS/cm), fair (750 < EC < 2,250 µS/cm), and poor (EC ≥ 2,250 µS/cm). EC varies from 170 to 41,747 with a mean value (standard deviation) of 2,625 (±3,465) µS/cm (Figure 2B). Based on EC classification, the groundwater is rated as excellent for irrigation in too few parts of Iran (≤0.05 by area), while it is poor in most other areas (≥56% by area). About 17% and 27% of Iranian territory, respectively, showed good and fair groundwater quality for irrigation with respect to EC. The maximum EC levels can be observed on the coasts of the Persian Gulf, Sea of Oman, and Caspian Sea, as well as in the country's central area and the shores of Lake Urmia.

The EC levels on the Persian Gulf coast are higher than that on the coast of the Sea of Oman, resulting from higher salinity and more evaporation in the former water body than the latter (Maghrebi et al., 2018). Based on TDS classification (WHO, 1993), the groundwater in around 73% of Iran’s territories is classified as permissible for agriculture-use, with TDS <3,000 mg/L. This means, however, that some parts of the country (around 27%) suffer from unsuitable groundwater sources for irrigation-use (Figure 2B). Based on TH, too few parts of Iran (around 0.5%) contain soft groundwater (TH ≤ 75 mg/L). Also, around 2.5% of the country's area have moderately hard (75 mg/L < TH ≤ 150 mg/L) and 26% have hard groundwater (150 mg/L < TH < 300 mg/L). The groundwater in most areas (around 71%) is classified as being too hard with respect to TH (TH > 300 mg/L) (Figure 2B).

The SAR levels indicate a certain ratio between sodium, calcium, and potassium, and are used as one of the comparative indicators of irrigation-use (Sayed & Wagh, 2011). In general, the higher the SAR, the lower water acceptability for irrigation. This is because using water with high SAR for a long time can replace water Na+ with K+ and Mg2+ in the soil. This process can reduce the ability of soil to form stable aggregate and permeability, and ultimately reduce the crop production capacity, especially in fine-grained soils (Holmes, 1995). The SAR varies from 0 to 67, with a mean (standard deviation) value of 4.7 (±5.8). Based on SAR classification, Iran’s groundwater irrigation suitability in about 70.6%, 11.2%, 18%, and 0.2% of the country is permissible for agriculture-use, with TDS <3,000 mg/L. This means, however, that some parts of the country’s area have moderately hard (75 mg/L < TH ≤ 150 mg/L) and hard groundwater (150 mg/L < TH < 300 mg/L). The groundwater in most areas (around 71%) is classified as being too hard with respect to TH (TH > 300 mg/L) (Figure 2B).

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category can be used in the event of a moderate amount of leaching. Water in the permissible to doubtful
category is only suitable for the irrigation of special plants with high salt tolerance (Etteieb et al., 2017). In
this case, the need for a proper drainage and leaching system is necessary. The doubtful to unsuitable cate-
gory is not suitable for irrigation on most land and plant species. Figure 4 shows that, while the excellent to
good category can be seen in just eight sub–basins (Anzali, Hamun, Hamun-Mashkil, Karkheh, Sefidrud,
Salt Lake, Sirjan, and Urmia Lake), the permissible to unsuitable can be seen in all sub-basins. The best
basins in terms of water suitability for irrigation-use are the basins adjacent to the Caspian Sea, such as
Anzali and Haraz. Lake Urmia, Central desert, Mehran, Saghand Desert, Sedij, Salt Lake, and Sirjan sub-bas-
ins have the highest number of points in the permissible to unsuitable categories. The use of groundwater
sources in these areas for agriculture can be associated with risks to soil and agricultural production. In
these areas, special plants, such as salt-resistant plants with a suitable irrigation system, should be selected.
3.3. Ionic Types and Hydrochemical Facies

For a better understanding of the country's groundwater hydrogeochemical facies, the analyzed samples were plotted on a Piper ternary diagram (Piper, 1944) for all 30 of Iran's sub-basins (Figure 5). We have also depicted the Piper diagram results on the map of Iran to better distinguish different water types in each sub-basin (Figure 6). Based on the triangular shapes in the Piper diagram, Ca\(^{2+}\) was the dominant cation in 7 out of 30 sub-basins, including Anzali, Garahi, Great Karoon, Haraz, Lut Desert, Qaresou, and the West Boundary River (Figure 6A). Na\(^+\) and K\(^+\) were dominant cations in three sub-basins, Atrak, Ghareghoum,
Figure 5. Piper diagram in Iran's sub-basins.
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Based on the anion shape section, four sub-basins can be identified by \( \text{HCO}_3^- \) (Anzali, Garahi, Haraz, and Sefidroud) and six by \( \text{Cl}^- \) (Atrak, Hamun, Hamun-Mashkil, Hirmand, and Hamun-Mashkil (Figure 6A). Seven sub-basins, Hamun, Hirmand, Patargan, Saghand Desert, Siahkooh Desert, Sirjan, and South-Balochistan, were mostly influenced by \( \text{Mg}^{2+} \) whilst no cation dominated in the other 12 sub-basins (Figure 6A). Based on the anion shape section, four sub-basins can be identified by \( \text{HCO}_3^- \) (Anzali, Garahi, Haraz, and Sefidroud) and six by \( \text{Cl}^- \) (Atrak, Hamun, Hamun-Mashkil, Hirmand,
Siahkooh Desert, and South-Balochistan) (Figure 6B). Most of Iran's sub-basins (20 out of 30 sub-basins) showed no dominant anion (Figure 6B).

The combined study of anions and cations in the diamond part of the Piper diagram showed no dominant water type (or mixed water type) in the majority of Iran's sub-basins (13 sub-basins) followed by sodium-chloride water type in nine sub-basins (the Central Desert, Gavekhouni, Ghareghoum, Hamun-Mashkil, Hirmand, Patargar, Siahkooh Desert, Sirjan, and South-Balochistan) (Figure 6C). Magnesium-bicarbonate and calcium-chloride water types were dominant in seven (Anzali, Bakhtegan, Haraz, Karkheh, Lut Desert, Qaresou, and Sefidroud) and one (Hamun) sub-basins, respectively (Figure 6C). Alkaline earth metals exceed alkaline elements in the sub-basins of Anzali, Bakhtegan, Garahi, Gevakhouni, Gorgan, Great Karoon, Hamun, Haraz, Helleh, Karian, Karkheh, Lut Desert, Mehran, Qaresou, Salt Lake, Sefidroud, Sefidroud, Lake Urmia, and the West Boundary River (Figure 6D). Also, weak acids exceed strong acids only in the Haraz, Qaresou, and Sefidroud sub-basins (Figure 6E).

4. Discussion

In the case of Iran groundwater resources, water salinity is the biggest obstacle for agricultural and drinking uses, making the salinity of the water more important than the water shortage itself, especially in central, eastern and southern parts of the country. In general, both naturally driven forces (e.g., climatic factors, geological characteristics, saline water intrusion to freshwater aquifers) and human disturbances contribute to Iran's groundwater deterioration (Barzegar et al., 2017; Chitsazan et al., 2019; Moghaddam & Najib, 2006; Rezaei et al., 2019; Samani & Moghaddam, 2015; Vesali Naseh et al., 2018).

With respect to naturally driven forces, it should be noted that Iran is a country located in an arid/semi-arid belt of the world, leading to evaporation of ~70% of the country's average rainfall volume annually and a dominance of deserts that cover ~20% of the country's area (Emadodin and Bork, 2012). Therefore, an obvious distinction exists between the groundwater chemical properties in the center, south and east, and the north and west (Figure 2). Lower average annual rainfall and higher evaporation rates in the center, east and south than those in the west and north contribute to the occurrence of saline groundwater in some parts of the center, east and south of the country (Figure 2). From a geological viewpoint, evaporitic and other saline geological formations (e.g., gypsum and halite) cover some parts of Iran's territory. These geological formations have a rapid dissolution rate that salinizes the groundwater resources especially in the central, southern and eastern parts of Iran (Figure 2) (Raesi et al., 2013). Groundwater deterioration in such geological formations depends on a wide range of different factors, such as type of evaporitic sediments with direct contact with water, residence time of water, ion exchange, and flow velocities (Aghazadeh & Moghaddam, 2011; Rahman et al., 2020). For example, due to natural rock-water interaction mechanism, groundwater resources in contact with halite deposits turn more saline than those in contact with gypsum rocks (Raesi et al., 2013). As concluded by Ayoubi et al. (2014), Narany et al. (2015), and Ebrahimii et al. (2016), the long residence time of water or dissolution of saline-rich minerals such as halite are major reasons for high Na⁺ content in the IGWR. In addition, the weathering and dissolution of carbonate mineral rocks such as limestone and dolomite by carbonic acid contribute to high concentration of Ca²⁺ in IGWR as shown in Figure 2 (Esmaili & Moore, 2012; Jalali, 2005; Tizro and Voudouris, 2008). Saline streams and saline inland lakes may also be linked to groundwater sources transversely, leading to the spread of salt-rich water into the aquifers. This is a naturally driven force that can deteriorate groundwater resources mainly in central, southern, northwestern, and eastern parts of Iran, where the saline streams and lakes are dominant. In this regard, Baghvan et al. (2010) showed an increasing hydraulic gradient between fresh and saline aquifers in the central regions of Iran, leading to groundwater salinization induced by saltwater intrusion. Vahidipour et al. (2021) concluded that the saltwater intrusion from the Bakhtegan Lake could threaten the groundwater resources in its coastal aquifers. Other studies also suggest the saltwater intrusion is a main contributor of groundwater degradation in different parts of Iran (e.g., Bahrami Jovein & Hosseini, 2017; Ebrahimii et al., 2016; Gorgij & Moghaddam, 2016; Noori et al., 2021; Ranjbar & Mahjouri, 2018).

In terms of human disturbances, agricultural practices can be considered to be a dire threat to the quality of groundwater sources (Mastrocicco et al., 2017; Oenema et al., 1998). This is particularly true for the irrigation needs in Mediterranean climate regions, where the high irrigation water demands overlap with
the dry season. As a consequence, Iran's agricultural expansion resulted in nonrenewable water harvesting due to the digging of a large number of deep and semi-deep wells (∼750,000 wells), leading to a catastrophic decline in groundwater levels across the country (Maghrebi et al., 2020; Noori et al., 2021). The overexploitation of groundwater has deteriorated the IGWR through salt-rich water intrusion induced by non-equilibrium hydraulic gradient between fresh and saline groundwater resources (Ebrahimi et al., 2016; Motallebian et al., 2019). A decline in the groundwater table can accelerate salt-rich water intrusion into the coastal aquifers (Gopinath et al., 2019; Jampani et al., 2020; Mondal et al., 2010; Naidu et al., 2013; Sankaran et al., 2012; Saxena et al., 2003; Surinaidu et al., 2015). This issue can be clearly seen in our study in the southern parts of Iran and the coasts of the Persian Gulf (Figure 2). Continuous seawater intrusion during the last decades has salinized the groundwater in the coasts of Persian Gulf. The change in annual average EC in some basins located in the coasts of the Persian Gulf was higher than other parts of Iran. These basins had reached to poor groundwater quality, which was just suitable for irrigation of salt-tolerant crops (Noori et al., 2021). The lack of operative drainage networks in agricultural lands that are responsible for ∼90% of national water consumption can also contribute to groundwater salinization (Emadodin et al., 2012; Ghorbani et al., 2017; Jafary & Bradley, 2018). Considering the high rate of evaporation in Iran, which can significantly increase solute concentration in the irrigation return-flow, this may be one of the main contributors to the country's groundwater deterioration. Also, cropland irrigation with untreated effluents can be considered as a main factor in the deterioration of the IGWR. According to a study conducted by Thebo et al. (2017), Iran was ranked among the countries with the highest irrigated croplands with untreated effluents, along with China, India, Mexico, and Pakistan. The untreated effluents with severe solute concentration can leachate and join the aquifers, leading to a decline in the country's groundwater quality. In addition, agricultural practices, such as the use of fertilizers, can severely worsen groundwater quality (Stigter et al., 1998). In Iran, more fertilizer is often used on agricultural lands than is actually needed by the plants. From the early 1990s to the early 2010s, the weight of chemical fertilizer used was doubled to increase the country's crop yields (Maghrebi et al., 2020). Agricultural practices along with heavy industrial activities may have changed groundwater acidity as well. In this regard, the minimum pH values were observed mainly in southwestern parts of Iran, the country's hub for both industry (e.g., oil and gas) and agriculture (Figure 2B). The acidic nature of water in this area is a result of anthropogenic pollution sources, such as sewage disposal, extreme fertilizer-use, and the infiltration of saline water that initiates the underlying geological weathering process (Ehya & Saeedi, 2019; Sangbari et al., 2018).

By considering the above, the spatial distribution of distinct hydrochemical facies across Iran (Figure 6) can be attributed to the degree of rock-water interaction, aquifer media, redox potential, and the degree of anthropogenic disturbances. In general, our findings reveal a distinctive relationship between Iran's geographical-geomorphological features and hydrochemical facies/groundwater quality. This information can be used in the formulation of new strategies and policies for Iran's groundwater quality management, while still considering other factors like agricultural and demographic parameters (e.g., population density, crops, and agricultural lands), groundwater and environmental health related issues. Given the close connection between groundwater depletion and quality, our investigation of Iran's groundwater hydrochemistry could offer insights to other countries facing the extensive groundwater depletion, especially those located in the Middle East (e.g., Pakistan, Saudi Arabia, and Syria).

5. Conclusion

In this study, using the information from 9,468 observation wells with mean annual data in 2011, groundwater quality conditions for drinking and irrigation purposes across Iran were examined. The results of this study showed about 40% of the samples tested for Na⁺, 0.2% for K⁺, 0.77% for Mg²⁺, 21% for Ca²⁺, 25% for Cl⁻, and 27% for HCO₃⁻ were above the standard threshold for drinking-use. The best sub-basins in terms of water suitability for agriculture-use were those adjacent to the Caspian Sea, such as Anzali and Haraz. Hydrochemical analysis revealed that there was no dominant water type in the majority of Iran's sub-basins (13 sub-basins). Nine sub-basins were dominated by a sodium-chloride water type, seven sub-basins by magnesium-bicarbonate, and one sub-basin by a calcium-chloride water type. The results of this study show the basic requirements for Iran's groundwater quality adaptation process, considering the water requirements for allocation to different purposes. Although this study answers important questions about
the spatial distribution of Iran's groundwater quality, its temporal trends across the country have remained unsolved. Examining this subject is suggested as a future research work.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The raw data used in our study are publicly available via Data Archive of the Iran Water Resources Management Company (IWRMC) in http://wrs.wrm.ir/amar/login.asp. This website is only available in Persian. The users should be first registered. Then, they can request any available data (groundwater data, surface water data, meteorological data, etc.) by selection of “Request Data” or in Persian: “رامآ تساواخرد” in their registered personal page.

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