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Hydrogeochemical Assessment and Regional Suitability Mapping of Groundwater for Irrigation Use in the Permian Basin, West Texas

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Abstract

Groundwater resources in West Texas, U.S.A., are the principal source of water for irrigation agriculture. However, its quality is under severe threat from both geogenic and anthropogenic sources. As a result, the quality of groundwater available to irrigators has had a significant impact on crop yield over the years, which makes it imperative to determine the variation in irrigation water suitability in the area. In this study, hydrogeochemical data from 127 groundwater samples obtained from the data base of Texas Water Development Board (TWDB) were analysed for irrigation suitability based on pH, percent sodium (%Na), Kelly ratio (KR), sodium adsorption ratio (SAR), magnesium adsorption ratio (MAR), soluble sodium percentage (SSP) and total dissolved solids (TDS). These samples were collected in five counties (Andrews, Gaines, Howard, Martin, and Midland) where agricultural activities are ongoing intensively. The pH, SAR, and SSP results, which ranged from 6.47 to 7.71, 0.49 to 13.34 meq/l, and 18.95 to 78.13 %, respectively, indicate that the groundwater samples are suitable for irrigated cropping. Although elevated levels of %Na were observed in a few samples in Andrews (max. value = 62%), Martin (max. value = 66%), and Howard (max. value = 70.44%) counties, irrigation suitability assessment based on %Na indicated that only 9% of the samples are "doubtful". KR and MAR content analysis show that 4.72% and 25.98% of the samples, respectively, are in a critical state, thereby rendering the groundwater resources in parts of Andrews, Martin, and Howard counties unfit for irrigation utilization. Groundwater indices recorded in Gaines County also show unacceptable levels of MAR that could be inimical to crop growth and productivity. According to TDS analysis, all samples exhibit severe potential limitations for irrigation use due to elevated mineral content in groundwater. No sample fell within the preferred category, with the highest TDS values occurring in groundwater samples that were collected in Andrews, Martin, and Midland counties. This is probably caused by geogenic factors resulting from the dissolution of carbonate and dolomite minerals in the Ogallala regional aquifer system, and partly by anthropogenic influences from the discharge of industrial effluents and the use of fertilizer. To ameliorate this, a groundwater management policy that takes cognizance of these factors should be adopted to improve the quality of water in the study area.

Keywords

Texas, Irrigation Suitability, Sodium Hazard, Crop Productivity, Groundwater

1. Introduction

Groundwater is a vital resource for the economic growth of the United States, serving as an important water supply for industrial, domestic, and agricultural uses (Lapworth et al., 2022). In Texas, over 20% of industrial and municipal water needs come from wells that tap into various groundwaters aquifer systems (Haque, 2023; TWDB, 2012). Most counties in eastern Texas primarily use groundwater for manufacturing, while the semi-arid western regions rely on it for municipal and irrigation needs (Udeh et al., 2024). Since the post-1940s period, marked by severe droughts, groundwater has supplied more than 1.23×10^{10} m^3 annually (TWDB, 2012). Of this, 80% is used for irrigation agriculture. Water use surveys from the Texas Water Development Board (TWDB) indicate that groundwater from the Ogallala regional aquifer system accounts for approximately 89-90% of the water used for irrigation in Texas, with an average total irrigation water use of about 1.17×10^{10} m^3 over 25 years (TWDB, 2012).

Water availability in Texas has become more unpredictable due to changing precipitation patterns, which may be linked to climate change, especially in the semi-arid regions of west Texas. This situation is worsened by multiple sources of contamination, such as lignite deposits, salt domes, and oilfield brine, which affect groundwater quality and lead to low crop yields and soil fertility issues. Studies have documented widespread nitrate contamination (Reedy & Scanlon, 2017), along with fluoride (Shaji et al., 2024) and saline intrusion (Chaudhuri & Ale, 2014), primarily in agricultural areas of west Texas, posing risks to groundwater used for irrigation. Over time, persistent hotspots of groundwater salinization, mainly due to high levels of sodium, sulfate, and chloride, have recurred in west Texas's semi-arid regions and the southern coastal plains. A combination of human activities and natural processes—including mineral dissolution, rock-water interactions, seepage from mineral-rich underground formations, evaporative enrichment, hydrocarbon exploration, salt dome dissolution, and saltwater intrusion—has contributed to increased groundwater salinity in the area. Additionally, reports of excessively high selenium levels in groundwater raise concern among farmers in west Texas (Hudak, 2009, 2010). Prolonged use of selenium-contaminated water for irrigation could harm soil quality and crop production (Al-Mashreki et al., 2023). Furthermore, contaminants in groundwater residues can stunt plant growth and cause nutritional deficiencies in crops, potentially affecting human health due to toxin presence in the food (Gaagai et al., 2023). Given these issues, thorough assessment, regular monitoring, and proactive forecasting of groundwater quality are essential for developing practical and economically feasible strategies to promote sustainable groundwater management and optimize irrigation practices (Ravindra et al., 2023).

Several techniques, viz., statistical (including machine learning), graphical, geospatial (use of GIS), and indexical (numerical), are commonly used in groundwater evaluation for irrigation use (Omeka et al., 2024). Amongst these, indexical techniques such as permeability index (PI), percentage sodium (%Na), Kelly's ratio (KR), residual sodium carbonate (RSC), electrical conductivity (EC), total dissolved solids (TDS) and sodium adsorption ratio (SAR) based on primary parameters (such as Mg^{2+}, Na^{+}, Cl^{-}, Ca^{2+} and K^{+}) are the most commonly used (Eid et al., 2023). Presently, the water quality index (WQI) has been known to be an effective method for assessing the quality of irrigation water (Ponsadailakshmi et al., 2018). Masoud et al. (2022) described WQI as a reliable, effective, and rapid tool for the holistic evaluation of irrigation water quality and highlighted a number of WQIs that are currently employed in assessing the suitability of groundwater for drinking, industrial, and irrigation purposes (Gaagai et al., 2023).

While previous works in east and west Texas have modeled the fluctuation of groundwater levels, determined the concentration levels of various contaminants in groundwater, assessed groundwater availability/potential and identified potential sources of groundwater contamination (Hudak, 2000; Alderman, 2001; Chaudhuri et al., 2012; Chaudhuri & Ale, 2014; Shaji et al., 2024), detailed assessments of suitability of groundwater for irrigation purpose in five counties (Andrews, Gaines, Howard, Martin and Midland) in west Texas, U.S.A is absent in previous literature. More so, no attempt has been made to model the variation by location in the quality of irrigation water in Andrews County, where varying levels of crop productivity have been recorded over the years (TWDB, 2012). This absence of a detailed assessment represents a major gap in understanding the influence of groundwater on the quality of soil and yield of crops in these areas.

Therefore, to address these gaps, the present study was conducted in areas of intense agricultural activities where crop cultivation is currently ongoing. For years, these semi-arid regions have relied extensively on groundwater for irrigation practices due to the scarcity of surface water resources. Recently, the high demand for irrigation water has raised concerns about the future, including the probability of deteriorating soil and groundwater conditions due to anthropogenic activities such as crude oil exploitation and animal waste disposal. Considering the adverse effects of climate change and the changing precipitation patterns in Texas, it is plausible to state that groundwater quality is likely to deteriorate, significantly impacting soil health and crop productivity. This study aims to assess the suitability of groundwater for irrigation purposes in five counties (Andrews, Gaines, Howard, Martin, and Midland) situated in west Texas, U.S.A. The specific objectives are: 1) to assess the suitability of groundwater for irrigation use; and 2) to determine the spatial distribution patterns of specific contaminants in the areas

2. Background

In the U.S, Texas (Figure 1) uses about 10% of its total national extracted groundwater, ranking it second in total groundwater withdrawals in the country, accounting for approximately 11% and 7.5%, respectively, of the country's total irrigation (2.3×10^7 m^3/day) and domestic (9.7×10^5 m^3/day) groundwater withdrawals (Chaudhuri et al., 2012).This puts Texas at the forefront of the agriculture industry in the U.S, with a total national agricultural output of 6.8% (Kenny et al., 2009). The main agronomic crop cultivated in Texas is cotton. In 2024, the United States Department of Agriculture (USDA) estimated an annual high cotton production rate of 15.1 million bales in Texas (USDA, 2024), which ranks it first in cotton production in the country.

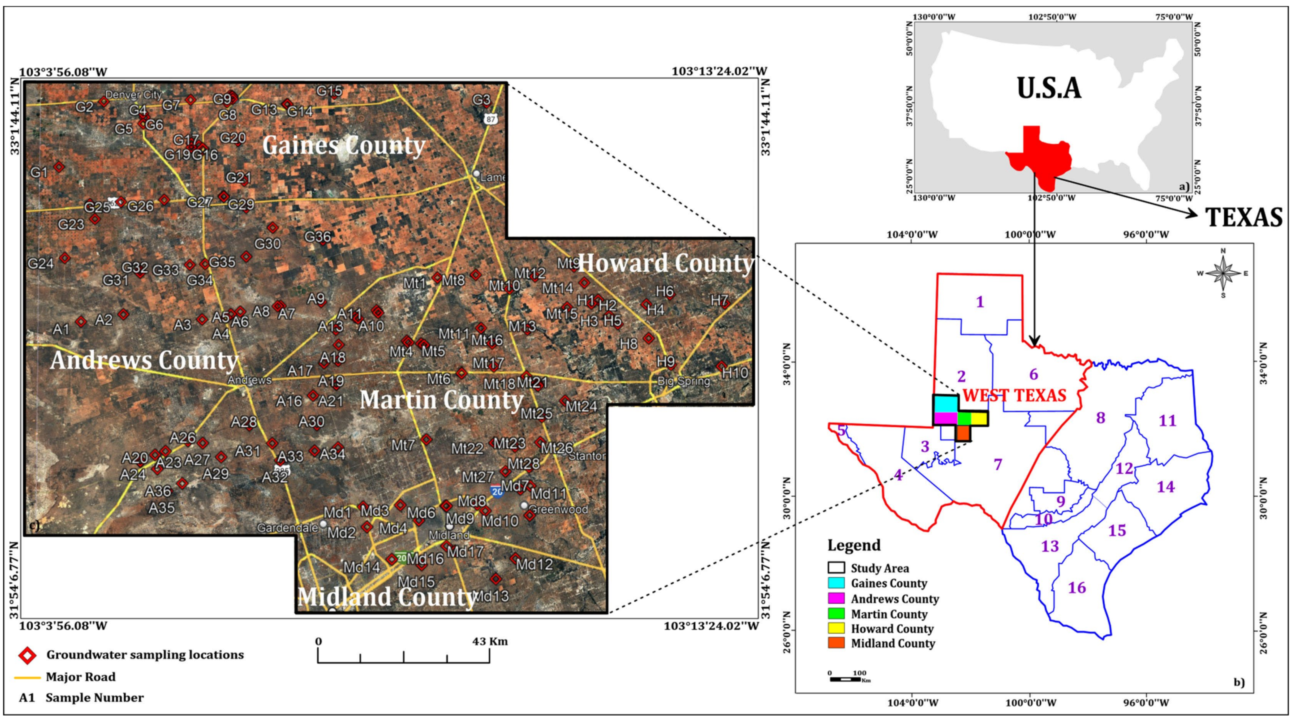

Figure 1. (a) Map of the U.S showing the state of Texas (adopted from Mirus et al., 2020) (b) Map of Texas showing the study area (five counties) in west Texas and the 16 Groundwater Management Areas (GMAs) (redrawn after TWDB, 2012) (c) Satellite imagery showing the spatial distribution of groundwater sampling points within each county.

To control subsidence caused by groundwater withdrawal as well as efficiently manage, protect, conserve, and preserve groundwater resources, Texas is partitioned into 16 Groundwater Management Areas (GMAs) (TWDB, 2012) (**Figure 1(b)**). These GMAs were initially designed to correspond with the spatial extents of the main aquifer systems in the state. Of the 30 aquifer systems that cover about 75% of the Texas landmass, only 9 are major aquifers (Guru & Horne, 2000). They provide more than 50% of the water consumed in the state (TWDB, 2012). The main aquifer systems, which are of Cretaceous to Quaternary age, are sedimentary in origin. A vast percentage of groundwater exploited from these aquifers is used for municipal (Hueco-Mesilla Bolson, Gulf Coast, Edwards-BFZ, Carrizo-Wilcox), livestock (Edwards-Trinity (High Plains)), and irrigation (Ogallala and Seymour) purposes. Seepage from adjacent geologic formations, irrigation return flow, and infiltration of precipitation recharge the major aquifers.

Groundwater extracted from this aquifer accounts for more than 25% of the total groundwater used for irrigated agriculture in the U.S and 80% of groundwater pumped for crop irrigation in Texas, and is, therefore, vital to the economy of the country (TWDB, 2015b; Leal et al., 2024).

While hydrocarbon seepage and farm pesticide waste are a concern nationwide, in locations where enclosed feeding of chicken, hogs, and cattle is common, animal dung has become a primary source of groundwater contamination. Currently, there are quite a number of potential sources of groundwater pollution. For instance, a good number of municipal waste removal units in Texas contain phosphates, inorganic contaminants, nitrates, pathogens, or other toxic substances that could leach into the groundwater system. All these could potentially render the groundwater unsuitable for irrigated agriculture.

3. Study Area & Geologic Setting

The study area (west Texas), which is bounded by latitude 32' and 33' north of the equator and longitude 101' and 104' west of the Greenwich meridian (**Figure 1(b)**), is underlain by the unconfined Ogallala aquifer system. The aquifer system has a shallow water table and consists of sand, clay, gravel, and silt. In the subsurface, it covers more than 9000 sq. miles from the Dakotas to Texas, with a maximum thickness of about 284 m (TWDB, 2015b).

The largest aquifer system (Ogallala aquifer) in the U.S is found within the Ogallala Formation (Chaudhuri et al., 2012; Rhodes et al., 2023) (**Figure 2**). In northwestern and west Texas, this aquifer provides irrigation water for 48 counties. It is the major aquifer that underlies these counties, where it covers a vast area in the subsurface.

The aquifer, which occurs mainly under water table conditions, comprises Tertiary sand, silt, clay and gravel, and is directly underlain and overlain, respectively, by the Triassic Dockum Group and the Quaternary Blackwater Draw Formation (**Figure 2(b)**). Sediments of the Dockum Group, which form the Dockum minor aquifer, consist of a sequence of alternating shales, conglomerates and sandstones

(Lehman & Chatterjee, 2005). Individual sandstone beds vary in thickness from a few meters to about 15 m and are commonly red, buff, light to dark, or greenish gray in color (George et al., 2011). The Blackwater Draw Formation, on the other hand, is made up of grayish-red, fine to medium, calcareous and silty aeolian sandstone, with a maximum thickness of about 30 m (Hall & Goble, 2020). It sits on the resistant seal rock caliche of the Ogallala Formation (**Figure 2(b)**). Water from several playa lakes in the region constitutes the major source of recharge for the Ogallala aquifer. Groundwater extracted from this aquifer is mainly used for irrigated agriculture. The Texas section of the aquifer has an average freshwater saturated thickness of about 30 m (Steiner et al., 2021).

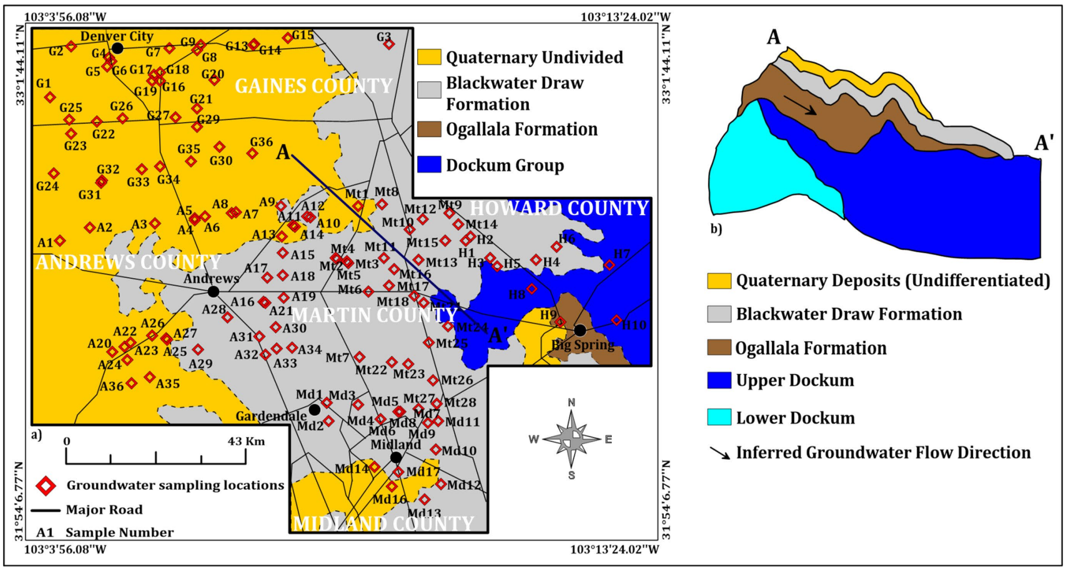

Figure 2. (a) Geological map of the study area showing groundwater sample locations (b) Schematic diagram of stratigraphic profile of geological units beneath A-A' (redrawn after Chaudhuri and Ale, 2014).

4. Materials & Methods

4.1. Groundwater Database

The groundwater division of the Texas Water Development Board supervises the measurement and monitoring of groundwater levels and chemical compositions in more than 100,000 spring and well locations in Texas. This information is stored in the database of the Water Information Integration and Dissemination (WIID) system of the board and is readily available to the public (www.twdb.texas.gov). Annually, measurements of some specific physico-chemical parameters of groundwater are conducted in about 8000 wells (this may vary depending on the socio-economic activities in the areas and/or the quantity of groundwater withdrawal in each county) throughout the state. The database of the TWDB also indicates the water-use category (industrial, commercial, unused, livestock, irrigation, public supply, domestic, etc.) for each well.

To assess the groundwater suitability for irrigation, some 127 groundwater samples were collected from different borehole wells in the study area by TWDB.

36 water samples were collected in Andrews and Gaines counties, while 28 locations were sampled in Martin County. A total of 10 and 17 samples, respectively, were collected from boreholes in Howard and Midland counties. The geographic coordinates of each well location are clearly indicated in the TWDB database, and the spatial coverage of the sampled sites is displayed in **Figure 2**. Before sample collection, the water in each well was pumped for 15 minutes, after which onsite measurements of temperature (˚C) and pH were conducted. The concentration values of major cations (Ca^{2+}, Mg^{2+}, and Na^{+}) and TDS (Total Dissolved Solids) were measured in the laboratory using the standard procedures outlined by the American Public Health Association (APHA) and approved by the TWDB. The concentration data of major cations, TDS, pH, temperature, sodium absorption ratio (SAR), and % Na were calculated/measured by the water quality department of the TWDB for the period from 2004 to 2024. We then used these data to calculate relevant irrigation water quality indices such as Kelly's ratio (KR), magnesium absorption ratio (MAR), and soluble sodium percentage (SSP) using the expressions given in **Table 1**, according to established methods for evaluating irrigation water quality.

Table 1. Equations applied in computing some relevant irrigation water quality indices.

Indices	Formula	Reference
KR	$\frac{Na^{+}}{\left(Ca^{2+}+Mg^{2+}\right)}$	Hakami et al. (2024)
MAR	$\frac{Mg^{2+}}{Ca^{2+}+Mg^{2+}}\times 100$	Vranešević et al. (2024)
SSP	$\frac{Na^{+}}{+Mg^{2+}+Na^{+}}\times 100$	Todd (1980); Dimple et al. (2022)

4.2. Irrigation Water Quality Indices

4.2.1. Sodium Adsorption Ratio (SAR)

Sodium Adsorption Ratio (SAR) is used to evaluate the potential threat to agricultural crop growth and productivity posed by the presence of sodium in groundwater systems used for irrigation (Hosseininia & Hassanzadeh, 2023). Elevated SAR concentration values in irrigation water samples facilitate the adsorption and binding of sodium molecules on soil particles, which results in the breakdown of soil structure. Consequently, the soil becomes hard and compacted when dry, thereby making it impermeable to water (Wang et al., 2023). SAR, expressed in milliequivalents per litre, is used to assess the relative concentration of sodium compared to magnesium (Mg) and calcium (Ca) in groundwater samples. The replacement of magnesium and calcium increases the concentration of sodium in irrigation water, which leads to the saturation of the ion-ex complex and dispersion of clay particles, thus degrading the soil's structure and composition (Singh et al., 2025). SAR values of the water samples from the counties have been computed by the TWDB.

4.2.2. Percent Sodium (Sodium Hazard)

Irrigation water is also classified based on the percentage of sodium (%Na). It is a crucial parameter, which, when low in value, also reduces the risk of water infiltration and aeration problems (Otmane et al., 2023). Irrigation water with a significantly low risk of water penetration problems is excellent for crop growth. Areas where irrigation waters of high to moderate %Na risk are employed in crop cultivation are commonly prone to loss of soil permeability/structure and usually require management interventions (Dimple et al., 2022). Values of %Na of groundwater samples collected in the study area have been calculated by the TWDB using the method of Wilcox (1955).

4.2.3. Kelly's Ratio (KR)

This indicator is essential for evaluating the quality of irrigation water by determining the threat posed by the water to soil degradation due to salinity and sodicity issues. In irrigated agriculture, KR values that are greater than unity suggest high water sodicity, indicating that the water is unsuitable for irrigation activities due to potential alkali hazards (**Table 2**) (Benouara et al., 2024). This index is calculated using the expression provided in **Table 1** above.

Table 2. Classification of groundwater for irrigation use (adopted from Hakami et al., 2024).

Indices	Range (mg/l)	Class	%
SAR	<10	Excellent	99.64
	10 - 18	Good	2.36
	18 - 26	Fair	-
	>26	Poor	-
%Na	20 - 40	Good	85
	40 - 60	Permissible	6
	60 - 80	Doubtful	9
	>80	Unsuitable	-
KR	<1	Suitable	70.87
	1 - 2	Marginal	24.41
	>2	Unsuitable	4.72
MAR	<50	Suitable	74.02
	>50	Unsuitable	25.98
SSP	0 - 20	Excellent	0.79
	20 - 40	Good	37
	40 - 60	Permissible	51.18
	60 - 80	Doubtful	11.02
	>80	Unsuitable	-

4.2.4. Magnesium Adsorption Ratio (MAR)

MAR is one of the relevant qualitative parameters for assessing the suitability of groundwater for irrigation. Increased magnesium levels in irrigation water are mainly caused by the high sodium exchange capacity of irrigated soils, which affects the uptake of essential nutrients (Paliwal, 1972; Choudhary & Satheeshkumar, 2018). According to Kumar and Singh (2015) and Krishna Kumar et al. (2017), excessive magnesium levels in irrigation water reduces crop yield and adversely impacts plant growth by increasing the alkalinity of the soil. This parameter was determined for all collected samples using the method of Vranešević et al. (2024) (**Table 1**).

4.2.5. Soluble Sodium Percentage (SSP)

This is a measure employed in evaluating the suitability of water for irrigation, specifically by assessing the potential for sodium to adversely impact soil properties (Alaya et al., 2014). It reflects the proportion of sodium ions relative to other cations in the water. Elevated SSP values can result in reduced soil permeability and negative effects on plant growth. The formula used in computing this index is expressed in **Table 1**.

The meaning, adopted values, and class range of each of these parameters are given in **Table 2**. Classification of groundwater quality for irrigation in each county was carried out based on these class ranges.

4.3. Software Package

In this study, we used a Geographic Information System (GIS) software, precisely Surfer version 23.0 software package. This tool expedited the production of 2D models showcasing the spatial distribution of the various irrigation groundwater quality indices that are relevant to this study. The distribution and variability of groundwater quality are visually represented in these maps in detail, which enhances our understanding of the suitability of groundwater for irrigation use in the study area.

5. Results & Discussion

The pH value of groundwater is a crucial parameter for ascertaining its suitability for irrigation purposes. In the study area, pH values of groundwater vary from 6.47 to 7.71, with average values ranging between 6.65 and 6.95 (**Table 3**). This suggests that the water samples are slightly basic to slightly acidic. The lowest pH value was reported in Howard and Martin counties, with samples in Andrews County having the highest pH value. The mild alkalinity exhibited by the samples could be attributed to dissolved carbonates within the Ogallala aquifer infiltrating into the groundwater. **Table 3** presents a summary of statistics, including the maximum, minimum, and average values of different irrigation water quality indices resulting from 127 groundwater samples collected in the five counties that make up the study area. According to Lovell (2023), the optimum range of pH values of groundwater required for irrigation use varies from 6.5 to 8.5 (Hakami et al., 2024). Only two samples, each from Howard and Martin counties, showed pH values below this safe range. This implies that 98.43% of the groundwater samples recorded pH values that fall within the acceptable range, indicating that the water is generally suited for irrigation use.

Table 3. Average, maximum and minimum parameter values used in evaluating the suitability of groundwater for irrigation in the study area.

	Parameter																				
	pH			KR			MAR (%)			%Na			SAR (meq/L))			SSP (%)			TDS (mg/l)		
County	Min.	Max.	Av.	Min.	Max.	Av.	Min.	Max.	Av.	Min.	Max.	Av.	Min.	Max.	Av.	Min.	Max.	Av.	Min.	Max.	Av.
Andrews	6.8	7.71	6.95	0.16	2.50	1.84	4.73	62.72	29.63	12.00	62.00	45.89	0.49	8.05	2.74	23.44	66.20	44.95	453	3857	1093.67
Gaines	6.82	7.60	6.93	0.15	1.33	0.67	20.80	62.02	45.14	18.00	51.00	29.82	1.08	4.94	2.12	23.69	62.23	38.82	229	1988	1004.42
Howard	6.47	7.58	6.71	0.44	3.39	1.40	14.40	57.40	33.75	25.00	70.44	45.74	1.35	11.31	4.45	30.88	77.27	53.64	511	6338	1636.47
Martin	6.47	7.53	6.65	0.21	3.57	1.20	14.04	68.14	38.75	13.00	66.00	42.28	1.00	13.34	4.11	18.95	78.13	48.74	658	4516	1529.39
Midland	6.63	7.41	6.92	0.40	1.57	0.76	10.07	48.07	27.31	27.00	54.00	35.78	1.16	5.30	3.4	28.62	61.13	41.82	442	3444.9	1379.56

5.1. %Na

With respect to the relative concentrations of cations in the irrigation water, assessment of percent sodium (%Na) in the groundwater samples revealed a worrisome range (12 - 70.44) exceeding permissible limits (60%) in 9% of the samples, all of which were taken from Andrews, Howard, and Martin counties (**Table 2**). **Table 3** shows maximum %Na of 62%, 70.44% and 66% for Andrews, Howard, and Martin counties, respectively. Elevated levels of %Na are, therefore, a serious concern mainly in Andrews County and partly in Howard and Martin counties. **Figure 3** shows %Na hotspot in the eastern and southern parts of Andrews County, suggesting that groundwater in these areas is not fit for irrigation purposes. The southeastern and northern portions of Martin and Howard counties, respectively, show small zones with slightly elevated %Na levels that could compromise the integrity of groundwater for irrigation use in these areas. This poses a great risk to crop productivity and soil health as Na bridges the pore throat, thereby reducing soil permeability, which impedes nutrient uptake and water movement (Salifu et al., 2017; Gautam et al., 2023).

Previous studies suggest that fertilizer use and/or carbonate mineral dissolution within the Ogallala aquifer could be the potential contributing factors (Chaudhuri & Ale, 2014). According to Hudak (2009), carbonate combined with excessive Na also increases the alkalinity of groundwater and could be probably responsible for the slightly higher pH values recorded in about 65% of the water samples. Notwithstanding, based on %Na values, 91% of the groundwater samples fall within the allowable limit (<60%) required for irrigation use (**Table 2**).

5.2. SAR

SAR values computed for the groundwater samples were found to range from 0.49 to 13.34 meq/L, implying that all the samples are good for irrigation agriculture (**Table 3**). The results show that 99.64% of the water samples fall in the "Excellent" range, while the remaining 2.36% fall in the "Good" range (Table 2). It is worth noting that areas with the highest values of SAR coincide with zones of elevated %Na (see Figure 3 and Figure 4). This makes it imperative for the crop-specific requirements of SAR to be considered before utilizing the groundwater for irrigation purposes in the southeastern and northern parts of Martin and Howard counties, where elevated concentrations of %Na were recorded.

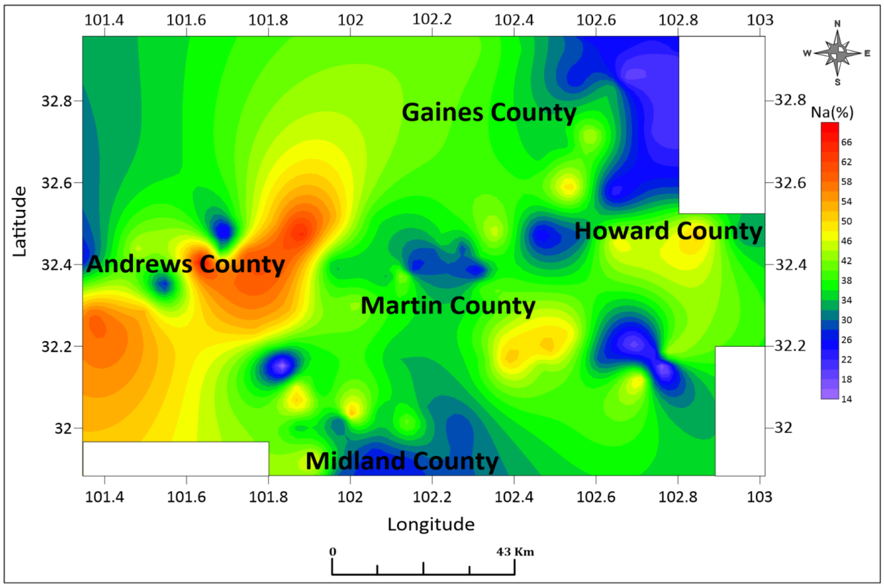

Figure 3. Spatial distribution map of %Na in groundwater samples collected in the study area.

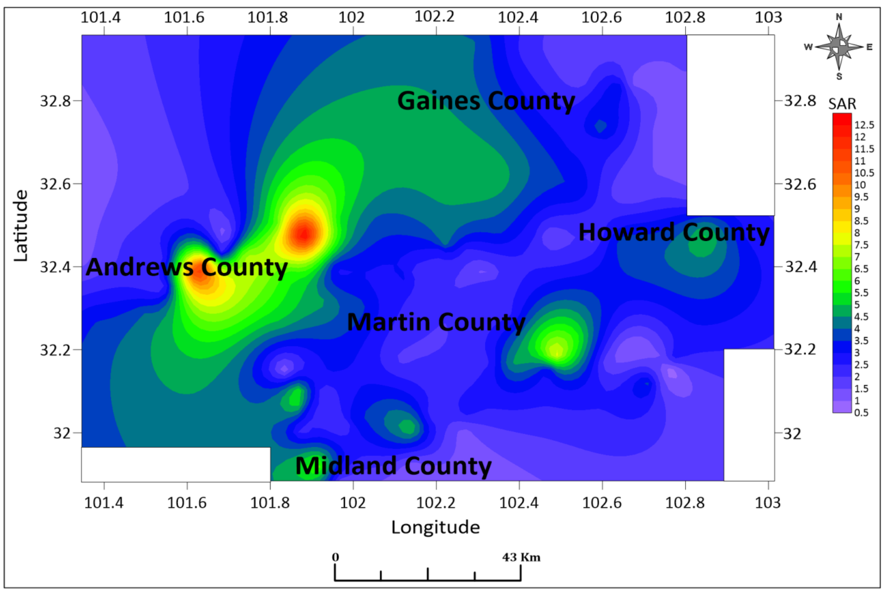

Figure 4. Spatial distribution map of SAR in groundwater samples collected in the study area.

5.3. KR

Overall, assessment of KR values, a critical index for the evaluation of irrigation water quality in agricultural provinces, revealed that 70.87% of the water samples are safe and fit for irrigation utilization (**Table 2**). However, 24.41% show marginal characteristics, while 4.72% are unsafe for use in irrigation agriculture due to alkaline hazards. This suggests that not all the water samples have good potential for irrigation use. According to the classification outlined by Kelly (1940) and Paliwal (1972), who proposed this parameter, groundwater with KR values exceeding unity is considered unsafe for irrigation purposes, while those with KR values less than 1 are deemed fit for irrigation utilization. Similar classifications have also been used by several authors in literature (Salifu et al., 2017; Zhang et al., 2025; Amwele et al., 2021; Thirumoorthy et al., 2024). Using the same classification, it implies that 29.13 % of the water samples collected in the study area are not recommended for irrigation. Specifically, 10 groundwater samples from Andrews County, representing 27.77% of the total samples collected in the county, have values above 1.0 and are unsuitable for irrigation purposes. Other areas with KR values greater than 1.0 make up 17.86% and 20%, respectively, of water samples taken from Martin and Howard counties and are considered undesirable for irrigation agriculture. These affected areas are located in the southeastern part of Andrews County, the northwestern and southeastern parts of Martin County, and the northern and northeastern axis of Howard County (**Figure 5**). These areas are indicated in **Figure 5**, which shows the spatial distribution of Kelly's ratio in the five counties.

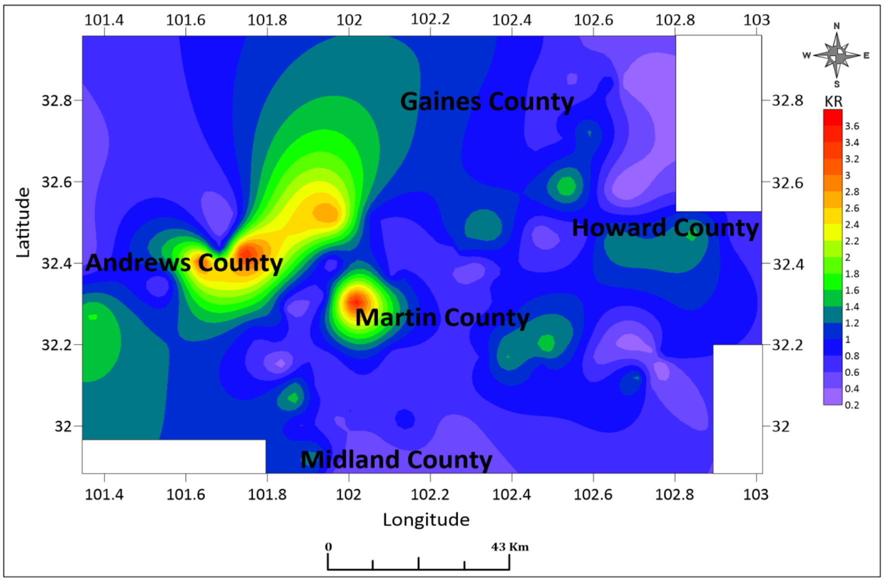

Figure 5. Spatial distribution map of Kelly ratio in groundwater samples collected in the study area.

5.4. MAR

Generally, 25.98% of the total samples pose a significant threat to soil structure and crop productivity based on MAR values (**Table 2**). Invariably, this indicates that only 74.02% of the samples, the majority of which were collected in Midland

County, are appropriate for irrigation agriculture (all samples taken from Midland County reported MAR values < 50 and are all suitable for irrigating crops). Excessive magnesium is indicated in 25% (9 samples), 41.67% (15 samples), 20% (2 samples), and 28.57% (8 samples) of the samples analyzed in Andrews, Gaines, Howard, and Martin counties, respectively. This poses a significant magnesium hazard to soil structure when using the MAR index. Besides anthropogenic discharges, the dissolution of dolomite minerals and carbonate cements in the Ogallala aquifer is a major contributor to the unacceptable levels of MAR in the counties. These affected areas include the northern and western parts of Gaines County, the southeastern parts of Andrews County, the northern and northwestern axis of Martin County, and the western corner of Howard County (Figure 6). Based on MAR values, Table 2 indicates that 34 samples analyzed in these areas have a deleterious impact on soil composition, which is inimical to soil fertility and crop yield.

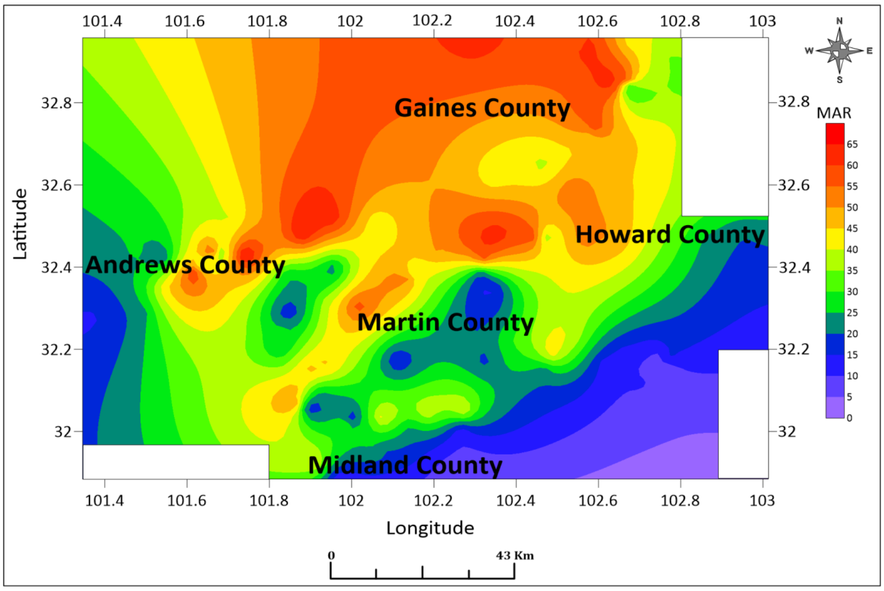

Figure 6. Spatial distribution map of MAR in groundwater samples collected in the study area.

5.5. SSP

SSP values range from 18.95 to 78.13% (Table 3). Of these, 0.79 % (1 sample) was classed as "Excellent", 37% (47 samples) was classed as "Good", and 51.18% was classed as "Permissible" (Table 2). No sample recorded SSP values above 80, which implies that all the samples are appropriate for irrigation agriculture. However, 14 water samples representing 11.02% of the total samples were classed as "Doubtful" (60 ≥ SSP ≤ 80). The spatial distribution map of SSP shows that the doubtful areas are located southeast of Andrews County, west and southeast of Martin County, and north and west of Howard County (Figure 7). These values highlight the need for continuous monitoring of groundwater in these areas and the importance of adjusting agricultural practices to mitigate any harmful effects on crops.

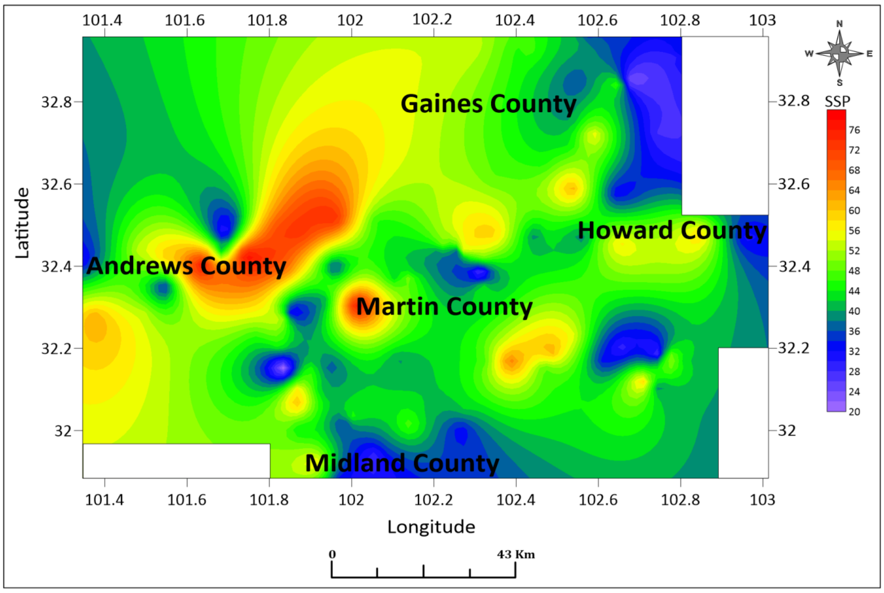

Figure 7. Spatial distribution map of SSP in groundwater samples collected in the study area.

5.6. TDS

In irrigated areas, measurements of TDS values in groundwater samples are essential to determine the rate of water uptake by crops and ensure that plant growth rates are not reduced. Based on the laboratory classification criteria of the US Department of Agriculture, various concentration levels of TDS in groundwater will have varying degrees of impact on the irrigation suitability of waters. The irrigation suitability of groundwater based on TDS is grouped as "Preferred for Irrigation" (<150 mg/l), Slightly to Moderately Preferred" or "Good to Doubtful" (150 - 1500 mg/l), or "Unsuitable for Agricultural Use" (>1500 mg/l). Although the results of this classification of irrigation water quality indicate that no sample was fit or preferred for irrigation, 42 samples (33.07%) were deemed unsuitable for agricultural utilization, while 85 samples (66.93%) were doubtful for irrigation use and show limited irrigation potential. The spatial distribution plot of TDS measurements of the samples show that majority of the unfit locations lie in the southeastern parts of Andrews County, the northwestern and southeastern parts of Martin County and the northern part of Midland County (Figure 8). A salinity problem will likely persist at the root zones of crops in these areas which could result in water stress for a prolonged period of time thereby leading to reduced crop growth.

While the parameters successfully assessed groundwater irrigation suitability; however, the analysis is limited by the wide temporal range, which obscures potential year-to-year variations in water quality. This study evaluated the overall water quality and its suitability for irrigated agriculture. The scope did not permit distinguishing anthropogenic and geogenic influences, which is a potential area for future investigation.

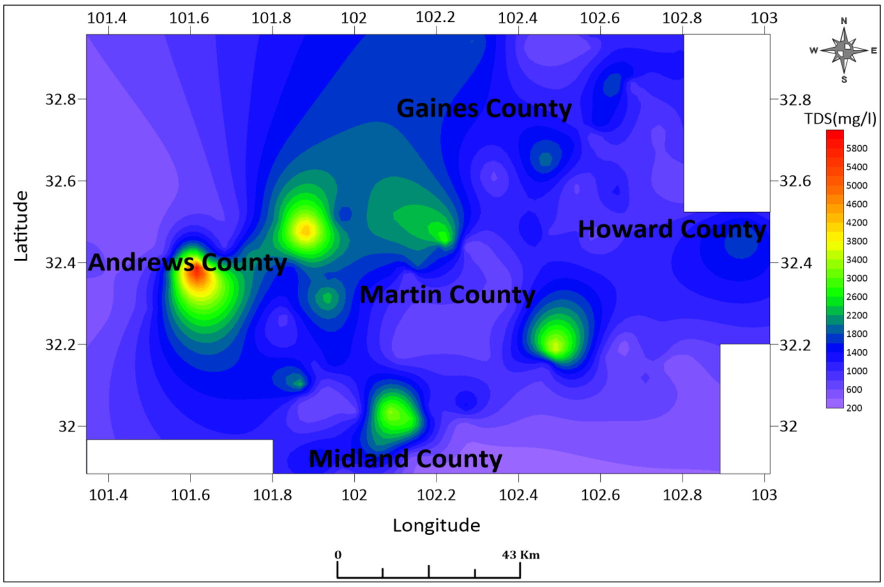

Figure 8. Spatial distribution map of TDS in groundwater samples collected in the study area.

6. Conclusion

This study has successfully analyzed the chemical composition of groundwater resources in five counties (Andrews, Gaines, Howard, Martin, and Midland) situated in west Texas, U.S.A., for their suitability and fitness for irrigation agriculture. A significant portion (9%, 4.72%, and 25.98%, respectively) of the 127 analyzed samples is not suitable for irrigation use in parts of Andrews, Martin, and Howard Counties based on %Na, KR, and MAR values, respectively. MAR values computed for 15 groundwater samples (41.67%) in Gaines are also undesirable for irrigation purposes. According to pH, SAR, and SSP values used in irrigation water suitability classification, all the samples from the five counties are suitable for irrigation agriculture, although the highest SAR values were recorded in the same areas where excessive %Na was reported. The TDS levels indicate that 33.07% of the samples, particularly from Andrews and Martin counties, are not appropriate for irrigated cropping. Of all irrigation suitability parameters determined in groundwater samples collected from Midland County, only TDS showed elevated concentration levels in 35.29% of the total samples, with an average value of 1379.56 mg/l. These findings underscore a clear degradation of water quality, especially in parts of Andrews, Martin, and Howard counties, where high levels of %Na, KR, MAR, and TDS were obtained. Collectively, these factors gradually diminish the irrigation water suitability in these counties, consequently impacting soil physical structure, plant growth, and crop yield. The persistent utilization of this compromised water in irrigation practices without taking cognizance of these factors will exacerbate sodicity and soil salinity, posing significant risks to groundwater quality and agricultural sustainability. To address these issues, an integrated water management strategy such as high-resolution monitoring of groundwater in identified hotspots areas, identification of potential contamination sources and adoption of integrated approaches like crop rotation with tolerant varieties to manage salinity. This secures the future of agriculture in the region and balances environmental preservation with agricultural needs is essential.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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