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Groundwater Quality Assessment for Irrigation in Durg District, Chhattisgarh, India: A Hydro Geochemical and GIS-Based Perspective

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Groundwater quality is a critical factor for agricultural irrigation, as its chemical composition can directly impact soil structure and crop productivity. This study investigates the groundwater quality in Durg district, Chhattisgarh, with a focus on its suitability for irrigation. A comprehensive analysis

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of hydro geochemical parameters such as pH, electrical conductivity (EC), sodium adsorption ratio (SAR), sodium percentage (Na%), residual sodium carbonate (RSC), and other key elements was conducted. The study uses both chemical analysis and digital tools such as ERDAS IMAGINE and MapInfo Professional to assess the spatial variability of groundwater properties and their implications for agricultural use. The results indicate that while groundwater quality in Durg district is generally favourable for irrigation, local variations exist that require consideration for optimal water use in agriculture.

Keywords: Groundwater quality; irrigation; hydro geochemistry; Durg district; Chhattisgarh; SAR; RSC; GIS.

1. INTRODUCTION

"Groundwater, the water stored beneath the Earth's surface in soil pore spaces and fractures of rock formations, is a critical natural resource that supports domestic, industrial, and agricultural activities worldwide. It constitutes approximately two-thirds of the world's freshwater resources and is especially vital for a country like India, where it fulfil a significant portion of water requirements. Groundwater is indispensable for ensuring food security, driving economic development, and meeting the needs of over 90% of the rural population and 30% of the urban population for drinking water (APHA, 2017). It also accounts for nearly 60% of the total irrigation potential in the country" (NRSA, 2008). However, rapid population growth, urbanization, industrial development, and the expansion of agricultural activities have led to a surge in groundwater demand.

The quality of groundwater is equally crucial as its availability, particularly for agriculture (Ambiga & Anna Durai, 2015). "The chemical composition of groundwater, influenced by factors such as recharge sources, geological interactions, and anthropogenic activities, determines its suitability for irrigation. Excessive salts or pollutants in groundwater can adversely affect soil health, crop yield, and overall agricultural productivity" (Michael, 2007; Gupta et al. 2020). Salinity, nutrient imbalance, and contamination from industrial and agricultural activities pose significant challenges to groundwater quality management (Rao, 2006). Thus, understanding the geochemical properties and temporal variations in groundwater quality is essential for sustainable resource utilization (Balachandar et al., 2010).

The application of modern technologies like Geographic Information Systems (GIS) has revolutionized groundwater studies (Balakrishnan et al., 2011). GIS enables efficient management, analysis, and visualization of spatially distributed data, making it a powerful tool for groundwater resource planning (Kumar et al., 2014; Nag & Das, 2014). By integrating geospatial data with hydro chemical analyses, GIS facilitates the identification of recharge zones, assessment of groundwater quality, and development of sustainable management strategies. These capabilities are particularly beneficial for addressing complex groundwater challenges and ensuring the long-term productivity of agricultural systems (Doneen, 1964; Jeihouni et al., 2014).

This research aims to evaluate groundwater quality and its suitability for irrigation using geochemical analysis and GIS techniques. The findings will provide valuable insights for planners and policymakers to develop effective strategies for sustainable groundwater resource management and agricultural development.

2. MATERIALS AND METHODS

This section describes the study area, data sources, methodologies, and analytical techniques employed.

2.1 Study Area

The study was conducted in the western-central part of Chhattisgarh, within the Durg district (Fig. 1). The area spans 646.8 km² and is located between latitudes 21°1'40.55"N to 21°21'56.03"N and longitudes 81°8'53.88"E to 81°25'37.02"E.

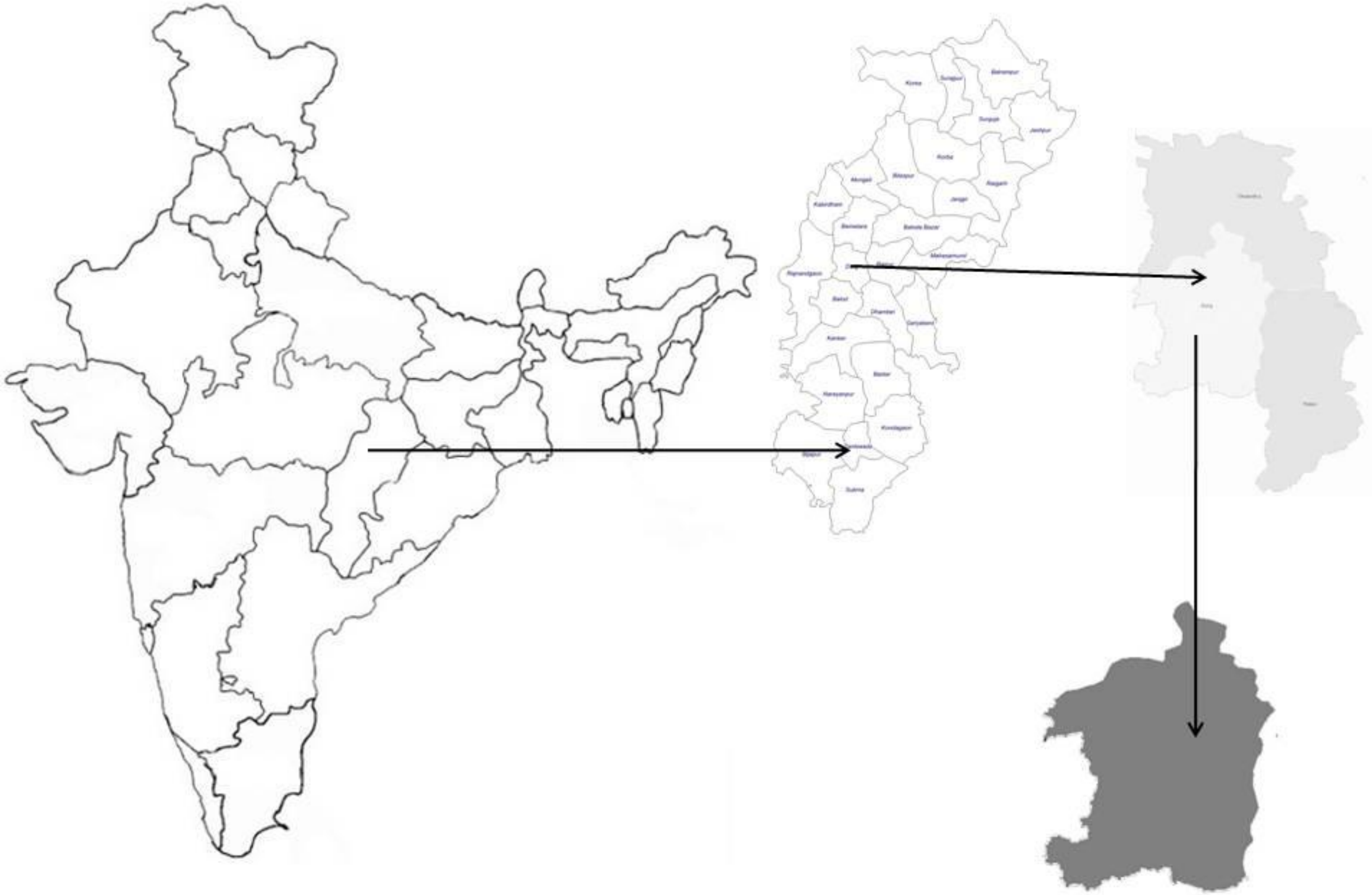

Fig. 1. Study Area

2.2 Climate

The region has a tropical climate. Temperatures rise from March to May, with May being the hottest month. The annual average rainfall is approximately 1052 mm, predominantly occurring during the monsoon season (June–September), with July recording the highest rainfall.

2.3 Data Acquisition

Survey of India (SOI) toposheets (f44p3, f44p4, f44p7, and f44p8 at a 1:50,000 scale) were used to prepare the base map. Groundwater quality data for 2013 were obtained from observation wells monitored by the Central Ground Water Board (CGWB), NCCR, Raipur, Chhattisgarh. The groundwater samples were analyzed in the NCCR laboratory for major ions using standard methods. Results are summarized in Table 1.

Table 1. Chemical analysis of sample data

S No.	Location	Lat.	Long.	pH	EC	TH	Na	K	Ca	Mg	HCO_3
1	Anda	21.1	81.3	7.5	1400	525	58	4.5	182	17	256
2	Durg	21.2	81.3	7.5	1593	670	40	4	230	23	98
3	Ganiyari	21.2	81.2	7.6	1127	465	21.7	1.3	122	38	244
4	Jeora-sirsa	21.3	81.3	7.7	788	310	38	18.2	104	12	195
5	Maroda	21.2	81.3	7.6	792	225	85	0.7	50	24	317
6	Konari	21.2	81.3	8	704	250	49.7	1	94	4	268
7	Kachandur	21.3	81.3	7.6	740	290	36	1.5	68	29	250
8	Utai	21.1	81.4	7.5	810	315	35.9	0.5	110	10	201
9	Bhilai	21.2	81.4	7.5	554	170	41.4	2.9	60	5	104
10	Ravelidih	21.3	81.3	7.3	578	250	15.5	0.6	78	13	128

Note: TDS – Total Dissolved Solids (mg/L); EC – Electrical Conductivity (S/cm); TH – Total Hardness (mg/L); Ca – Calcium (mg/L); Mg – Magnesium (mg/L); Na – Sodium (mg/L); K – Potassium (mg/L); CO_3^{2+} - Carbonate (mg/L); HCO_3^- – Bi- Carbonate

2.4 Software

- **Operating System:** Microsoft Windows 8.1 Pro
- **GIS Software:** ERDAS IMAGINE 9.1, MapInfo Professional 11.0

2.5 Methodology

Conversion of Concentrations

To convert concentrations from mg/L to meq/L, the following formula was applied:

$$meq/l \quad = \frac{mg/l}{Eq\ wt}$$

2.6 Groundwater Suitability for Irrigation

The following indices were used to assess groundwater suitability for irrigation:

1. **Sodium Adsorption Ratio (SAR):** It indicates the degree to which irrigation water tends to enter into cation-exchange reactions in soil (Hakim et al., 2009). Sodium replacing adsorbed calcium and magnesium is a hazard as it causes damage to the soil structure and becomes compact and impervious. SAR is defined as:

$$SAR \ = \frac{Na}{\sqrt{(Ca + mg)/2}}$$

where, all the ionic concentrations are in meq/l.

2. **Percent Sodium (%Na):** Sodium concentration plays an important role in evaluating the groundwater quality for irrigation as sodium increases the hardness of the soil and reduces its permeability (Kelly et al., 1940). The SSP valus are calculated using the formula given below:

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

where, all ionic concentrations are expressed in meq/L.

3. **Residual Sodium Carbonate (RSC):** An excess amount of sodium bi-carbonate and carbonate is considered to be detrimental to the physical properties of soils as it causes dissolution of organic matter in the soil, which in turn leaves a black stain on the soil surface on drying. This excess amount is denoted by Residual Sodium Carbonate (RSC) and is calculated by the following formula:

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

where, all the ionic concentrations are expressed in meq/L.

4. **Kelly's Index (KI):** In Kelly's Ration (KR), sodium is measured against calcium and magnesium to determine the suitability of irrigation water. When KI is >1, it indicates higher sodium and vice versa. KI is calculated by using the formula:

$$KI = \frac{Na}{Ca + Mg}$$

5. **Permeability Index (PI):** The soil permeability is affected by long-term irrigation influenced by Na^{+}, Ca^{2+}, Mg^{2+} and HCO_3 contents of the soil. The permeability index values also indicates the suitability of groundwater for irrigation. PI is calculated as follows:

$$PI = \frac{(Na + \sqrt{HCO_3})*100}{Ca + Mg + Na}$$

where, all ionic concentrations are expressed in meq/L.

2.7 Digital Image Processing

Digital Image Processing is a collection of techniques for the manipulation of digital images by computers (Michael & Ojha, 2013). The raw data received from the imaging sensors on the satellite platforms contains flaws and deficiencies. To overcome these flaws and deficiencies in order to get the originality of the data, it needs to undergo several steps of processing.

2.7.1 Data import

Satellite imagery was imported into ERDAS IMAGINE for pre-processing.

2.7.2 Geo-referencing

Geo-referencing was performed using Google Earth coordinates and ERDAS IMAGINE 9.1 to align spatial data with real-world locations.

2.7.3 Image mosaic

Individual raster datasets were merged to create a composite image.

2.7.4 Subset extraction

A region of interest was extracted from the composite image using ERDAS Imagine's subset tool.

2.7.5 Map preparation

Contour lines representing equal elevations were generated to illustrate topographical features.

3. RESULTS AND DISCUSSION

Hydrogeochemical properties govern the behavior of dissolved chemical constituents in groundwater (Subramani et al., 2012). These constituents, present as ions, molecules, or solid particles, undergo various reactions and redistributions among ionic species. The chemical composition of groundwater is influenced by rock weathering processes and evolves over time and space. The concentration levels of hydrogeochemical constituents determine the water's utility for agricultural purposes.

3.1 Irrigation Water Quality Parameters

Table 2 presents the irrigation water quality parameters for the study area, including pH, Electrical Conductivity (EC), Sodium Adsorption Ratio (SAR), Soluble Sodium Percentage (SSP), Residual Sodium Carbonate (RSC), Kelly's Index (KI), and Permeability Index (PI).

3.2 Groundwater Quality Assessment

The suitability of groundwater for irrigation was evaluated based on established standards, as summarized in Table 2.

Table 2. Irrigation water quality parameters

S.no.	Location	EC	pH	SSP	EC	SAR	RSC	%Na	SSP	RSC	KI	PI%
1	Anda	1400	7.5	19.37	1400	1.1	-6.3	20	19.37	-6.3	0.24	35.1
2	Durg	1593	7.5	11.49	1593	0.67	-11.78	12	11.49	-11.78	0.13	19.87
3	Ganiyari	1127	7.6	9.28	1127	0.44	-5.23	10	9.28	-5.23	0.1	28.94
4	Jeora-sirsa	788	7.7	21.07	788	0.94	-2.99	25	21.07	-2.99	0.27	43.88
5	Marauda	792	7.6	45.23	792	2.47	0.72	45	45.23	0.72	0.83	73.13
6	Konari	704	8	30.05	704	1.36	-0.64	30	30.05	-0.64	0.43	59.21
7	Kachandur	740	7.6	21.29	740	0.92	-1.69	22	21.29	-1.69	0.27	48.83
8	Utai	810	7.5	19.8	810	0.88	-3.02	20	19.8	-3.02	0.25	42.82
9	Bhilai	554	7.5	34.54	554	1.38	-1.71	35	34.54	-1.71	0.53	59.59
10	Ravelidih	578	7.3	11.94	578	0.43	-2.87	12	11.94	-2.87	0.14	37.61

Table 3. Classification of Samples according to Standards specified for Water Quality Indices

Parameters	Range	Class	Number of sample	% of sample
EC	< 250	Excellent	0	0
	250 - 750	Good	4	40
	750 - 2000	Permissible	6	60
	2000-3000	Doubtful	0	0
	> 3000	Unsuitable	0	0
SSP	< 20	Excellent	3	30
	20 - 40	Good	6	60
	40 - 60	Permissible	1	10
	60 -80	Doubtful	0	0
	> 80	Unsuitable	0	0
RSC	< 1.25	Low		
	1.25 – 2.5	Medium		
	> 2.5	High		
SAR	0 - 10	Excellent	10	100
	10 -18	Good	0	0
	18 -26	Permissible	0	0
	> 26	Doubtful	0	0
MAR	≤ 50	Suitable	10	100
	> 50	Unsuitable	0	0
KI	< 1	Suitable	10	100
	> 1	Unsuitable	0	0

3.2.1 pH

The pH of groundwater in the study area ranged from 7.3 to 8.0, with an average of 7.65, indicating slightly alkaline water suitable for irrigation (Fig. 2).

3.2.2 Electrical conductivity (EC)

The EC ranged from 554 to 1593 µS/cm, with an average of 1073.5 µS/cm. These values classify 40% of the samples as "Good" and 60% as "Permissible" for irrigation use (Fig. 3).

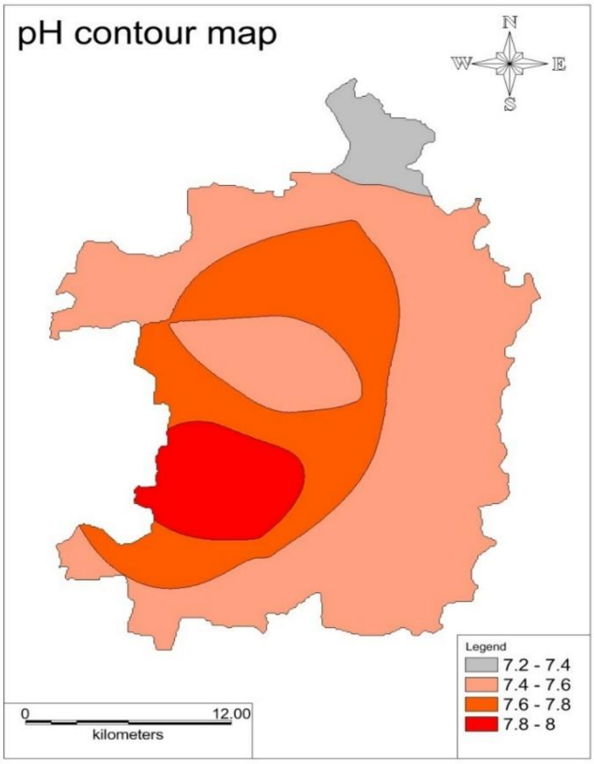

Fig. 2. Spatial Distribution of pH

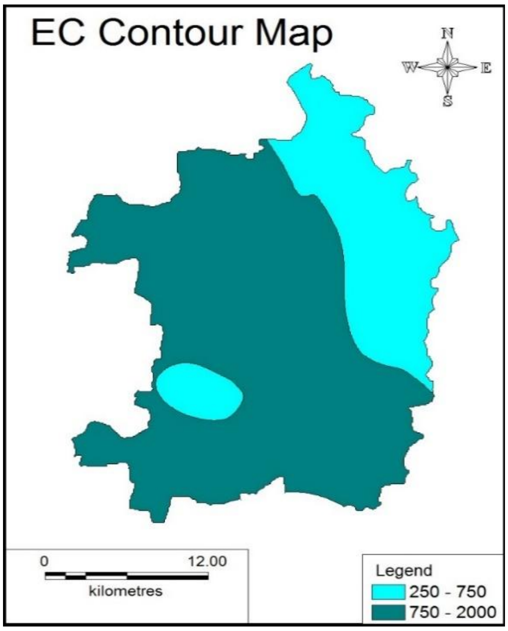

Fig. 3. Spatial Distribution of EC

3.2.3 Sodium adsorption ratio (SAR)

SAR values indicate the extent to which sodium is absorbed by the soil (Shah & Mistry, 2013). Groundwater with high sodium and low calcium can saturate the cation-exchange complex with sodium, which may lead to the dispersion of clay particles and damage the soil structure. The SAR values in the study area ranged from 0.43 to 2.47. Based on the SAR classification, 100% of water samples fall into the excellent category, making the groundwater suitable for irrigation on almost all soils (Fig. 4).

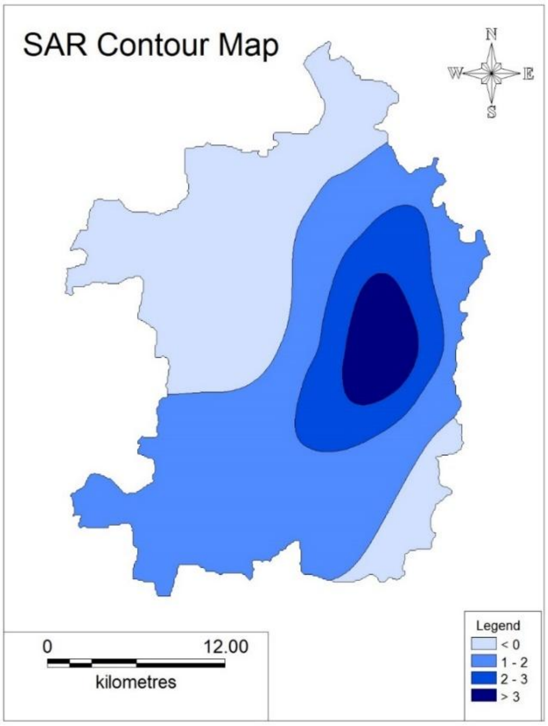

Fig. 4. Spatial Distribution of SAR

3.2.4 US salinity laboratory diagram

To assess the suitability of groundwater for irrigation, the US Salinity Laboratory (1954) classification system is based on SAR and EC. This diagram classifies irrigation water into 16 groups, such as C_1S_1, C_2S_2, S_2C_1, S_2C_2 etc. Based on SAR values, all water samples from the study area have low sodium hazard. Plotting the samples on the US Salinity Diagram reveals that they fall within the C_2S_1 and C_3S_1 classes, which indicate that the water is moderately suitable for irrigation. C_1S_1, C_2S_2, S_2C_1, S_2C_2 etc. Based on the SAR values, all samples have low sodium hazard and on plotting over the U.S. Salinity diagram the water samples of study area fall in the C_2S_1 classes and C_3S_1 classes and hence can be considered moderately suitable for irrigation (Fig. 5).

3.2.5 Percent sodium (%Na)

Percent Sodium in groundwater is an important parameter for determining water suitability for irrigation. Higher sodium content can negatively affect soil permeability. The %Na values in the study area ranged from 10% to 45%. Of the samples, 30% fall in the excellent class, 60% in the good class, and 10% in the permissible class. The spatial distribution map indicates that areas classified as "Excellent to Good" cover 267.05 km², while areas classified as "Good to Permissible" cover 366.89 km² (Fig. 6).

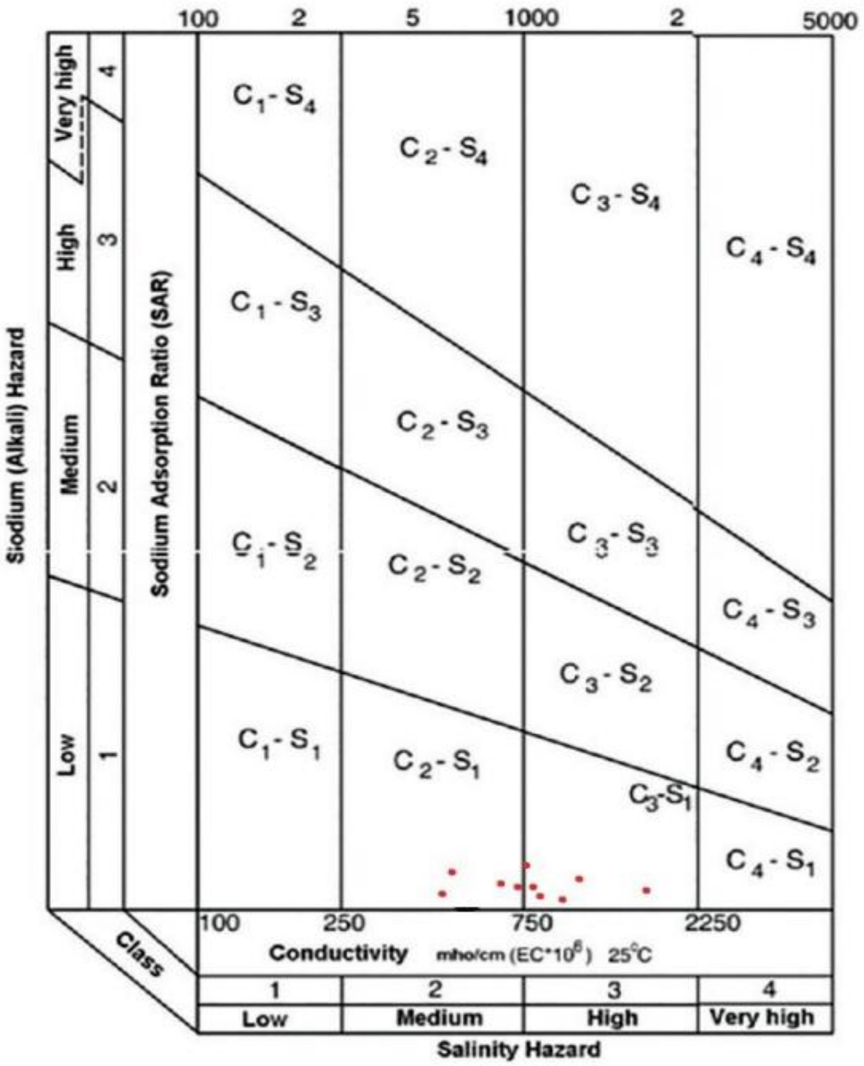

Fig. 5. US Salinity Diagram

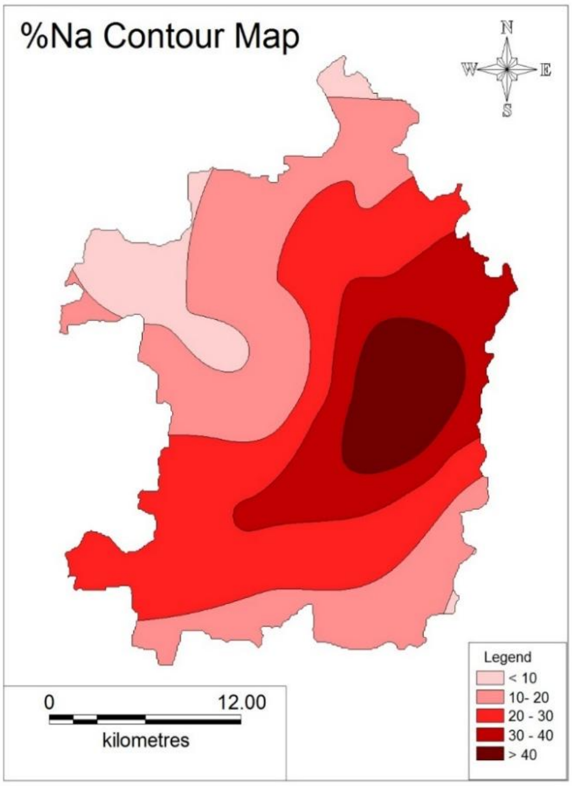

Fig. 6. Spatial distribution of %Na

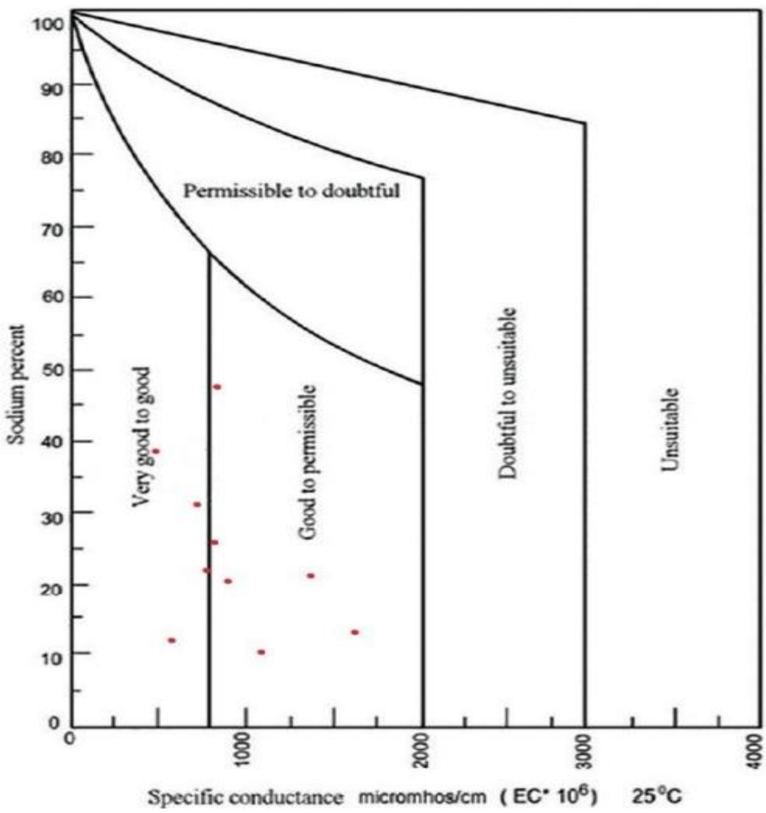

Fig. 7. H. Wilcox's Diagram

3.2.6 H. Wilcox's diagram

The H. Wilcox (1955) diagram is another method for determining the suitability of groundwater for agricultural use based on %Na (Wilcox,1955) because Na+ concentration reacts with soil to reduce its permeability (Todd, 1980). The groundwater samples in the study area show that 4 samples fall under the "Excellent to Good" category, while 6 samples fall in the "Good to Permissible" category for irrigation use.

4. SUMMERY AND CONCLUSION

The hydrogeochemical analysis of groundwater in the study area indicates that it is generally suitable for irrigation, with most samples exhibiting favorable properties. The pH values range from 7.3 to 8.0, reflecting slightly alkaline conditions, while EC values classify water as "Good" to "Permissible." Sodium Adsorption Ratio (SAR) and Percent Sodium (%Na) confirm excellent to good suitability for irrigation, with SAR values indicating minimal risks of soil dispersion. Spatial analysis highlights variability across locations, with most samples falling under C2S1 and C3S1 classes in the US Salinity Laboratory Diagram, affirming moderate irrigation suitability. Although a few locations exhibit elevated EC or %Na levels, the overall water quality supports agricultural use. Regular monitoring and sustainable management practices are essential to mitigate risks and ensure long-term groundwater usability for irrigation.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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