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Groundwater Quality Assessment for Sustainable Water Management In Semi-Arid Chitradurga District, Karnataka

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ABSTRACT

Groundwater pollution reduces water quality and negatively impacts human well-being, social and economic development, and agricultural land value. Therefore, to evaluate the pre-monsoon groundwater quality in Chitradurga district, Karnataka, 55 randomly collected pre-monsoon (February- March, 2023 & 2024) bore well water samples from farmlands across different villages in Hiriyur, Hosadurga, Challakere, Chitradurga, Molakalmuru, and Holalkere taluks were analyzed for pH, EC, Ca, Mg, Na, K, SO_4, CO_3, HCO_3, Cl, and B. The samples were also tested for Total Hardness (TH), Total Dissolved Salts (TDS), Soluble Sodium Percentage (SSP), Sodium Adsorption Ratio (SAR), Residual Sodium Carbonate (RSC), Kelley' s Index (KI), Permeability Index (PI), Magnesium Hazard (MH), Potential Salinity (PS), and Water Quality Index (WQI). Results showed that WQI ranged from 30 to 81, with 87% of samples recording less than 50, indicating excellent water quality; 13% recorded between 51 and 81, indicating good quality for drinking. Similarly, irrigation suitability revealed that SAR indicates excellent to good. SSP indicates good to poor, RSC indicates good to bad, and PI indicates good. KI indicates permissible to non-permissible. The MH ranged from 60-98.65, indicates 100 % of water samples are non-acceptable. PS indicates excellent to good and to injurious. It was concluded that for drinking water samples are excellent to good. For irrigation, 66 % of water samples need to be treated before irrigation to cropland to control soil sodicity and salinity, sodium and sodium carbonates hazards, as it recorded RSC >2.5. Also, 100% of groundwater samples are found to have magnesium hazard, thus it leads to alkalinity/sodicity upon irrigation, which needs suitable irrigation water management practices, thereby elevating crop production and productivity and maintaining soil health and quality, besides controlling chemical land degradation.

1 | INTRODUCTION

Freshwater scarcity worsened by pollution, growth, urbanisation, industrialisation, and agriculture. Groundwater makes up 30% of the world's fresh water and 0.76% of total water, with 99% of fresh water stored underground (Upmanu *et al*., 2020). In India, groundwater is vital for drinking, irrigation, and industry, with about 230 km³ used annually (Kaliraj *et al*., 2019). It supplies 65% of irrigation needs (NDTV, 2019), mainly for its affordability and lower pollution risk. Over 2 billion people depend on groundwater (Famiglietti, 2014). In semi-arid regions, it is the main water source for drinking and farming. In arid areas like Chitradurga, deep aquifers supply irrigation. 70% of groundwater use is for agriculture (NGWA, 2021). Groundwater potential is declining, notably in drylands (Douville *et al.*, 2021).

Contamination of groundwater comes from various sources, including sanitation systems, landfill leachate, wastewater treatment effluents, leaking sewer systems, petrol stations, hydraulic fracturing (fracking), and the widespread use of chemical fertilizers in agriculture, as well as naturally occurring pollutants like arsenic and fluoride (Michael, 2014). Using this polluted groundwater for drinking or farming poses serious risks to human and animal health. Additionally, in coastal areas, groundwater is at risk of saltwater intrusion, which can cause land subsidence. These problems are worsened by rising sea levels and the diverse impacts of climate change, especially on the water cycle. Furthermore, groundwater extraction has led to a shift in the Earth's axial tilt of up to 31 inches (Mindy, 2023; Davide, 2023). Therefore, assessing groundwater quality is essential, as pollution is often invisible and harder to clean up compared to surface water bodies like rivers and lakes.

When surface water undergoes significant evaporation, groundwater can become saline, either naturally in endorheic regions or artificially in irrigated agricultural areas. In coastal regions, extracting groundwater can lead to salinization. The variation of groundwater salinity across different locations results from diverse hydrogeological characteristics, which pose risks to groundwater in specific areas. Elevated salinity levels make water unsuitable for drinking and irrigation, especially in coastal regions like Bangladesh and parts of East and West Africa (Tanjila *et al.*, 2023). As water moves through the landscape, it accumulates soluble salts, mainly sodium chloride, which are left behind during evapotranspiration. In low-lying irrigated areas, poor soil and surface aquifer drainage can cause a shallow water table, sometimes reaching the surface. Waterlogging and increasing salt concentrations in surface waters contribute to soil salinity and land degradation (Anon, 2010), negatively impacting local economies and ecosystems (Ludwig *et al.*, 1993). In semi-arid regions like the Chitradurga district, aquifers with surface irrigation face higher salinisation risks due to excess irrigation water seeping into the ground from wells (ILRI, 1989).

The chemical composition of subterranean water is affected by the mineral components of the rocks and aquifer it traverses. Various hydrogeochemical processes modify the chemical makeup of groundwater as it moves from one aquifer to another, causing spatial and temporal variations in its hydrogeochemical characteristics. These variations depend on the geological and chemical properties of the aquifer (Hwang *et al.*, 2017). Understanding groundwater composition and evaluating it are essential for determining its suitability for various applications. Therefore, in this study, the groundwater from Hiriyur, Hosadurga, Challakere, Chitradurga, Molakalmuru, and Holalkere taluks of Chitradurga district, Karnataka, has been characterized and assessed for its suitability for drinking and irrigation purposes on a sustainable basis. The objectives are: i) to characterize the groundwater of Chitradurga district, Karnataka, by analyzing the concentrations of different major cations and anions; ii) to evaluate the groundwater for drinking suitability using the water quality index (WQI); iii) to assess its suitability for irrigation through parameters such as total dissolved salts (TDS), soluble sodium percent (SSP), sodium adsorption ratio (SAR), residual sodium carbonate (RSC), total hardness (TH), Kelly's index (KI), potential salinity (PS), magnesium hazard (MH), and permeability index (PI); and iv) to discuss irrigation water management in Chitradurga district, Karnataka, India.

HIGHLIGHTS

- Water Quality Index ranged from 30-81, indicating that it's excellent to good quality for drinking.
- Magnesium Hazard ranged from 60-98.65, indicating that 100% of the groundwater is unacceptable for direct irrigation.
- Spatial analysis revealed Na^+-K^+-Cl^--HCO_3- dominated groundwater chemistry with high salinity requiring improved drainage and water management practices

2 | MATERIALS AND METHODS

2.1 | Study Area

Chitradurga district belongs to Central Karnataka, a hot, moist semi-arid eco-sub-region and a hot arid eco-sub-region, and as per the Planning Commission, Agro-Climatic Region is the Southern Plateau and Hills Region (10), covering a total geographical area (TGA) of 8.433 lakh ha. The district lies between north latitude of 13º 32' 20.721" to 15º 3' 27.178" N to east longitude of 75º 58' 55.046" to 77º 55' 57" E with an altitude of 732 m AMSL. It receives rainfall from June to September, primarily from the southwest monsoon, and from October to December, primarily from the northeast monsoon. Average yearly rainfall varies between 668 mm in Holalkere in the west to 457 mm in Chellakere in the northeast. The temperature varies between 17 to 41 ^{0}C and may fall up to 12 – 9 ^{0}C during the winter season. Geology is granite, gneiss & schist. Storage of groundwater in hard rock terrain and its movement control by the lineaments and fractures of the area (Basavarajappa *et al.*, 2015). The land is used for coconut, areca nut, maize, finger millet, Bengal gram, jowar, sunflower, cotton, tomato, onion, banana, mango, sapota, mulberry, pomegranate, and chrysanthemum cultivation. The vegetation consists of Prosopis sp., Lantana, tamarind, Acacia sp., neem, and cacti. Agriculture is a significant economic activity in rural livelihoods using water sources from canals, tanks, borewells, rivers, and rainfall.

2.2 | Water Sample Collection and Analysis

A total of 55 random bore well water samples were collected from different farmlands of Hiriyur and Hosadurga (27 samples collected during February-March, 2023) and Challakere, Chitradurga, Molakalmuru and Holalkere taluks (28 samples collected during February-March, 2024) during the pre-monsoon period (*Fig. 1*). Collected water samples were labelled with coordinates and stored in polyethylene bottles, which were brought to the laboratory, refrigerated, and used for further laboratory characterization. Major cation and anion concentrations were determined in all the water samples using standard protocols outlined by APHA et al. (2012). pH and EC were analyzed using a pH meter (Hanna make) and an EC meter (Toshniwal make), respectively. The Ca^{2+}, Mg^{2+}, Na^+, and K^+ were analyzed by an atomic absorption spectrophotometer (Pinnacle 900 F by PerkinElmer). The CO_3^{2-} and HCO_3^- were estimated via acid titration, and Cl^- by the Mohr technique of silver nitrate titration. The BaCl method was applied for SO_4^{2-} determination using a UV-VIS spectrophotometer. Boron estimation was done by the Azomethine-H method (Keren, 1996).

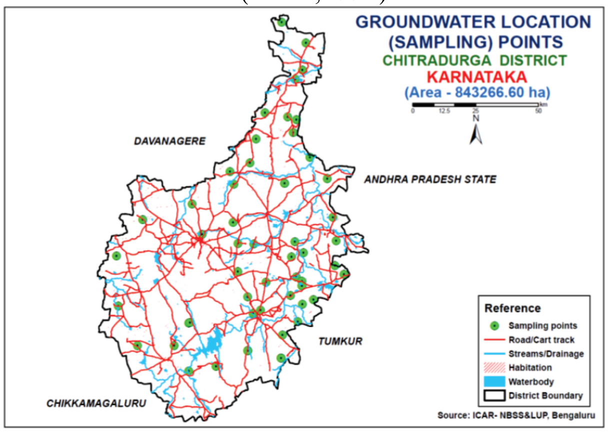


FIGURE 1 Groundwater location (sampling) points in Chitradurga district

2.3 | Preparations of different water quality diagrams, maps and figures

Piper diagrams (Piper, 1944), Wilcox (Wilcox, 1955), log Wilcox and riverside diagrams (USSL, 1954) were created for assessing groundwater qualities using Diagram 8.3 software. The Gibbs diagram (Gibbs, 1970) was prepared using MS Excel 2019. Pearson's correlation analysis of the water quality parameters was done by R Studio V 4.3.2 using the metal package, indicating ns, i.e. non-significant at p >= 0.05; significant at p <0.05 = r*; significant at p < 0.01= r**; and significant at p <0.001 = r ***. ArcGIS 10.7.1 software was used for making a geographical pattern of groundwater quality attributes in the investigation extent.

2.4 | Determinants of different water quality assessment parameters

2.4.1 | Water Quality Index (WQI)

WQI was computed in four levels (Ramakrishnaiah *et al.*, 2009). At the first level, all 9 water quality parameters have been assigned a weight (ai) based on their priority/ importance among all the quality parameters (Table 1) for drinking purposes. The highest weight of 4 has been given to pH, SO_4, and TDS, and the lowest weightage of 2 to Ca, Mg, and TH. In level two, relative weight (Ai) is computed from equation (1)

$$Ai = ai \,/\, \sum_{i=1}^{n} ai \ldots\ldots\ldots\ldots (1)$$

Where Ai indicates relative weight, ai indicates the weight of the parameter, and n is the total number of parameters. Relative weight (Ai) values calculated for individual parameters are presented in Table 1. At the third level, a rating scale for quality (wi) for individual parameters is assigned by dividing the concentration (Ci) of each water sample by its corresponding standard (Si), as per the procedure outlined in BIS, and then multiplying by 100.

$$wi = (Ci / Si) \times 100 \ldots\ldots\ldots\ldots (2)$$

Where wi indicates the quality rating, Ci represents the concentration of each individual water chemical parameter in mg l^{-1} for every water sample, while Si denotes the Indian drinking water typical for a parameter, also measured in mgl^{-1}

At the fourth level, the WQI was computed by calculating SIi, which is obtained by multiplying the already calculated Ai by wi, and then summing all the SIi to result in the WQI, as mentioned below in Equations 3 and 4.

$$SIi = Ai \times wi \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$$WQI = \sum_{i=1}^{n} SIi \ldots\ldots\ldots\ldots\ldots (4)$$

SIi indicates the subindex of the ith parameter; Ai indicates the relative weight and quality rating of the i^{th} parameter, and n indicates the total number of parameters.

Based on the computed WQI values, water quality was classified into five classes: excellent, good, poor, very poor, and unsuitable for drinking, corresponding to WQI values of <50, 50-100, 100-200, 200-300, and >300, respectively.

TABLE 1 Relative weight of water chemical parameters.

Water Chemical Parameters	Indian Standards	Weight (ai)	Relative weight (Ai)
pH	6.5-8.5	4	0.167
Ca mgl^{-1}	75-200	2	0.083
Mg mgl^{-1}	30-100	2	0.083
SO4 mgl^{-1}	200-400	4	0.167
HCO3 mgl^{-1}	244-732	3	0.125
Cl mgl^{-1}	250-1000	3	0.125
TH	300-600	2	0.083
TDS	500-2000	4	0.167

2.4.2 | Total Hardness

TH was estimated by the below-mentioned equation 5 (Todd 1980) and expressed as mg/l of $CaCO_3$.

$$TH = 2.497 \times Ca^{2+} + 4.115 \times Mg^{2+} \ldots\ldots\ldots\ldots (5)$$

TH (mg l^{-1}) values up to 600 and up to 100 are permissible recommended limits for drinking purposes as per BIS (2012) and WHO (2004), respectively.

2.4.3 | Total Dissolved Salt (TDS)

TDS indicates the total dissolved solids present in the water, and it was empirically determined from electrical conductivity values (µS/cm) and expressed in mg l_{-1} as per Equation 6 below.

$$TDS\ (mg/l) = 0.67 \times Conductivity\ (\mu S/cm) \ldots\ldots\ldots\ldots\ldots (6)$$

Groundwater samples as per TDS (Davis & De Wiest, 1966) values are classified as < 500, 500-1000, <3000, and >3000 as desirable, permissible, useful, and unfit for drinking and irrigation, respectively.

2.4.4 | Soluble Sodium Percentage (SSP)

SSP indicates the ratio of sodium to total cation multiplied by 100. A high sodium (Na+) percentage depletes the soil's permeability, thereby affecting plant growth. It can be calculated using Equation 7.

$$SSP = [(Na^{+} + K^{+}) / (K^{+} + Na^{+} + Ca^{2+} + Mg^{2+})] \times 100 \ldots\ldots\ldots (7)$$

SSP values <20, 20-40, 40-60, 60-80, and >80 are considered excellent, good, permissible, doubtful, and unsafe, respectively, for irrigation.

2.4.5 | Sodium Adsorption Ratio (SAR)

SAR indicates the proportion of concentration of sodium

(Na^+) ions to calcium (Ca^{+2}) and magnesium (Mg^{+2}) ions in a water sample, and it can be calculated as per equation 8 below.

$$SAR = Na^+/[(Ca^{+2} + Mg^{+2})/2]^{0.5} (meq/l) \quad (8)$$

Based on SAR values, water quality for irrigation suitability was done; if SAR values are <10, 10-18, 19-26, >26 are classified as excellent, good, doubtful, and unsuitable for irrigation, respectively.

2.4.6 | Residual Sodium Carbonate (RSC)

The surplus concentration of CO_3^{2-} and HCO_3^- anions in groundwater over the total of calcium (Ca^{+2}) and magnesium (Mg^{+2}) cations concentration is defined as residual sodium carbonate (RSC).
RSC is calculated by the following equation 9.

$$RSC = (HCO_3^- + CO_3^{2-}) - (Ca^{+2} + Mg^{+2}) \quad (9)$$

If the RSC value is <1.25, up to 2.5, and >2.5 is suitable, marginally suitable, and unfit for irrigation, respectively (Lloyd & Heathcote, 1985).

2.4.7 | Kelley's Index (KI)

The estimated sodium concentration, alongside calcium and magnesium concentrations, is referred to as the KI value (Kelly, 1940), which can be calculated using Equation 10 below.

$$\text{Kelly index} = Na^+/(Ca^{+2} + Mg^{+2}) \quad (10)$$

If KI is >1 indicates high sodium content, then it is unsuitable for irrigation, whereas <1 is suitable for irrigation use. However, SAR is more generally applicable to identify sodium hazards than KI.

2.4.8 | Permeability Index (PI)

The soil permeability is influenced by the long-term irrigation and is affected by sodium (Na^+), calcium (Ca^{+2}), magnesium (Mg^{+2}), and bicarbonate (HCO_3^-) contents of the soil. PI is calculated by equation 11

$$PI (meq/l) = [(Na^+ + \sqrt{HCO_3^-})/(Ca^{2+} + Mg^{2+} + Na^+)] \times 100 \quad (11)$$

According to PI, Doneen (1964a) categorized water into three categories: Class I, Class II, and Class III. Class I indicates 100% maximum permeability, making it suitable for irrigation; Class II indicates 75% maximum permeability, which is marginally suitable; and Class III indicates 25% maximum permeability, rendering it unsuitable for irrigation, respectively.

2.4.9 | Magnesium Hazard (MH)

A higher content of magnesium is formed due to the presence of exchangeable sodium in irrigated agricultural soils. Paliwal (1972) announced the MH and computed as per equation 12.

$$MH (meq/l) = [Mg^{2+}/(Ca^{2+} + Mg^{2+})] \times 100 \quad (12)$$

An MH value greater than 50% is not suitable for irrigation, as it affects crop yield and soil structure.

2.4.10 | Potential Salinity (PS)

Potential salinity indicates the concentration of chloride ions (Cl^-) plus half of the sulphate (SO_4^{2-}) ions; it can be calculated as shown below (Doneen, 1964a) in equation 13.

$$PS (meq/l) = Cl^- + 1/2So_4^{2-} \quad (13)$$

Based on PS, water quality can be classified as excellent to good, good to injurious, and injurious to unsatisfactory if PS values are <5, 5-10, and >10, respectively.

3 | RESULTS AND DISCUSSION

3.1 | Chemical Formulation and Spatial distribution of Ground Waters, Chitradurga district

The results presented in Table 2 indicate the chemical properties of the groundwater, and Fig. 3 illustrates the spatial distribution of groundwater parameters. The pH ranged from 7.49 to 9.06, with a mean of 8.38. Approximately 51 % of the water is alkaline in reaction, with a pH above 8.5, and the permissible limit (BIS, 2012) for drinking purposes (Table 3). Gypsum present in the aquifer rock may be diluted, leading to higher salinity (Chaudhary & Satheeshkumar, 2018). The electrical conductivity ranged from 764 to 4400 µS/cm with a mean of 1599 µS/cm, indicating that the higher concentrations of cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) and anions (SO_4^{-2}, CO_3^{-2}, HCO_3^{-1}, Cl^{-1}) present in groundwater samples are contributing to medium to very high salinity. More than 66 % of water has very high salt concentrations. Higher EC might also due to weathering of aquifer minerals and human activities (Tanaya, 2024).

Among major cations, Na^+ content recorded higher concentrations, which varied from 41.50 to 790.80 with a mean of 205.08 mg l^{-1} followed by Mg^{2+} concentrations (17.14-135.32 mg l^{-1}), Ca^{2+} (1.31-55.23 mg l^{-1}), and the lowest content is K^+ (ranged from 0.34 to 79.25; a mean of 4.46 mg l^{-1}). Calcium content is <200 mg l^{-1}, which is within the permissible limit. Magnesium was also within the permissible limit (<100 mg l^{-1}) except for five water samples. The potassium content varied from low to high, and approximately 53 % of the samples were high (> 2 mg l_{-1} in K^+). Sodium concentration was high (>200 mg l^{-1}) in 38 % of the samples. Among anions, Cl^{-1} and HCO_3^{-1} recorded higher contents, which varied from 78.10-795.20 mg l^{-1} and 134.20-500.20 mg l^{-1}, respectively, followed by SO_4^{2-} (6.08-134.40 mg l^{-1}) and CO_3^{2-} (18-90 mg l^{-1}). Chlorine and Sulphate were recorded < 1000 mg l^{-1} and <400 mg l^{-1}.

Fig. 2 shows major cation and anion concentrations in groundwater, which indicates the relative proportion of ion concentrations in the order for cations: $Na^+ > Mg^{2+} > Ca^{2+} > K^+$ and anions: $HCO_3^{-1} > Cl^{-1} > SO_4^{2-} > CO_3^{2-}$. Na^+ and Mg^{2+} and HCO_3^{-1} and Cl^{-1} are the major causes of elevated levels of pH and EC in the district. The spatial distribution (*Fig. 2*) shows that sodium and potassium contents are higher in the northern part of Chitradurga, which is an arid region, due to high evaporation. This may also be attributed to tube wells with deeper depths and lower discharge rates. Groundwater investigations indicated that aquifers are present between the depths of 15 mbgl and 200 mbgl in the Chitradurga district, and bore wells drilled to a depth in the district ranged from 64 mbgl to 200 mbgl (CGWB, 2013).

However, boron concentrations were medium to high in the southern parts, a semi-arid region, which is due to sequential deposition of transported solutes in semiarid conditions. Among cations, Na^+ was the highest constituent, and K^+ was the lowest, which might be due to the low rate of weathering of potassic rocks, whereas in anions, Cl^- was the major constituent, and $SO4^{2-}$ was the lowest constituent, which might be due to the reduction of sulphate in the aquifer system. The correlation study (*Fig. 4*) shows that CO_3^{2-} is significantly strongly correlated with B (r^{***} = 0.47). pH is strongly negatively correlated with B (r^{***} = -0.72) and CO_3^{2-} (r^{***} = -0.53). EC was strongly positively associated with Mg^{2+} (r^{***} = 0.66), Na^+ (r^{***} = 0.83) and Cl^{-1} (r^{***} = 0.87), indicating that major salts in the groundwater are NaCl and $MgCl_2$. Cl^{-1} was strongly positively associated with Mg^{2+}(r^{***} = 0.70) and Na^+ (r^{***} = 0.74), demonstrating those ions are derived from either halite (NaCl) or $MgCl_2$ sources. Na^+ significantly positively interrelated with Mg^{2+} (r^{**} = 0.40), HCO_3^{-1}(r^{**} = 0.41) and SO_4^{2-}(r^{**} = 0.38) indicating that which are derived from soil Na_2SO_4 and $NaHCO_3$ sources.

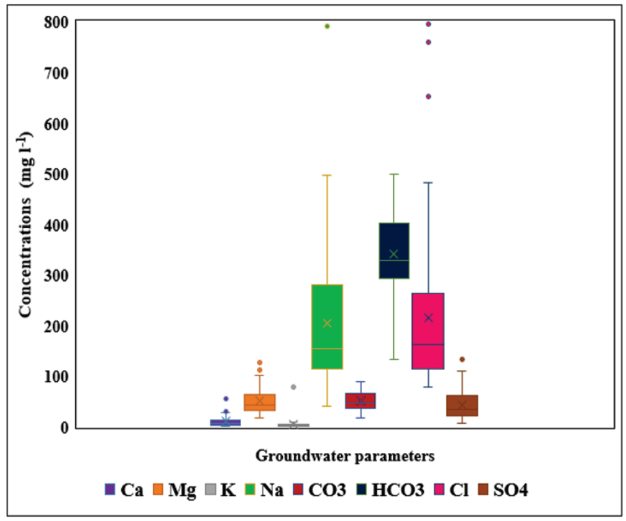
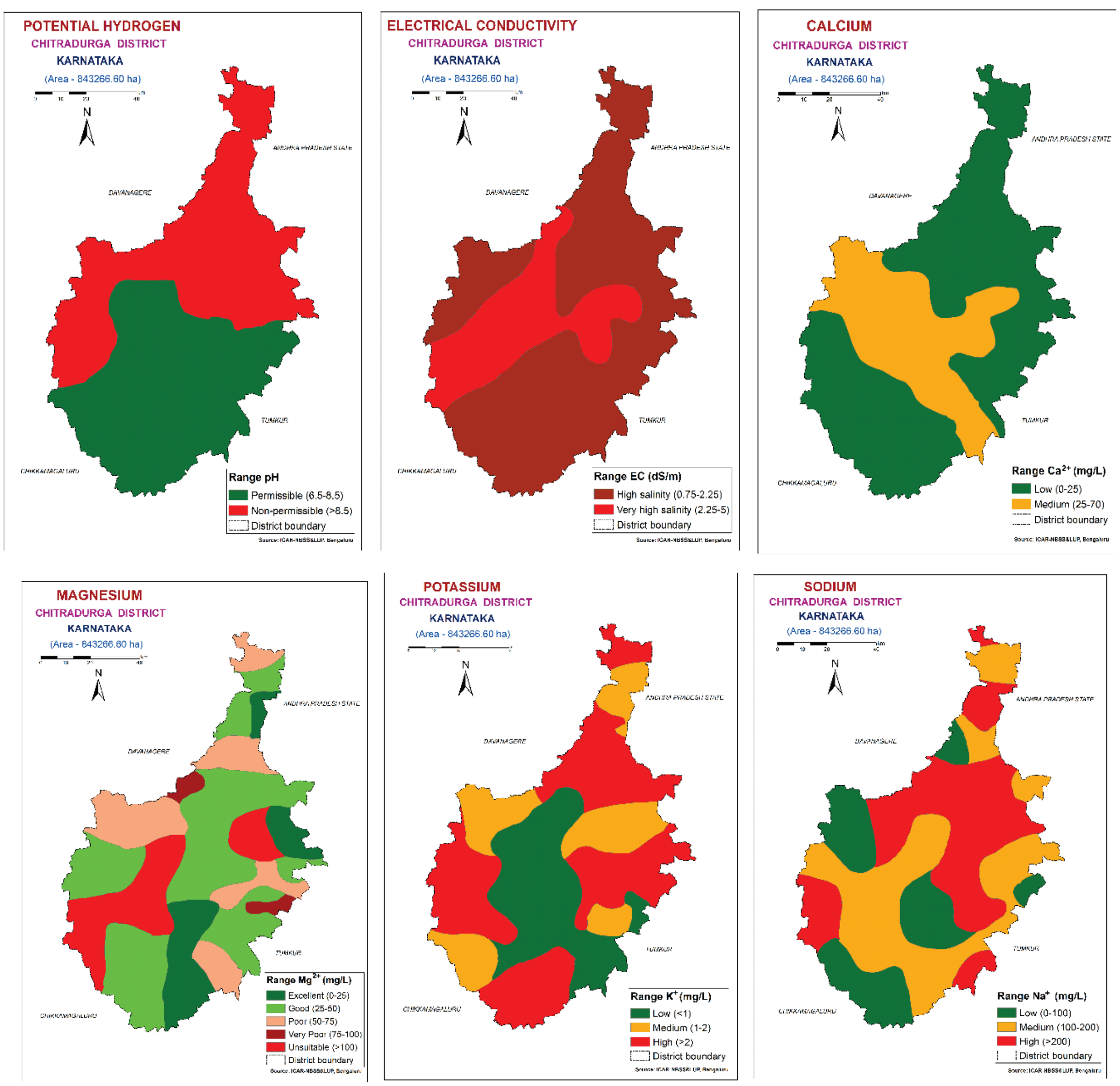


FIGURE 2 A box plot illustrating the concentrations of main cations and anions in groundwater within the Chitradurga district



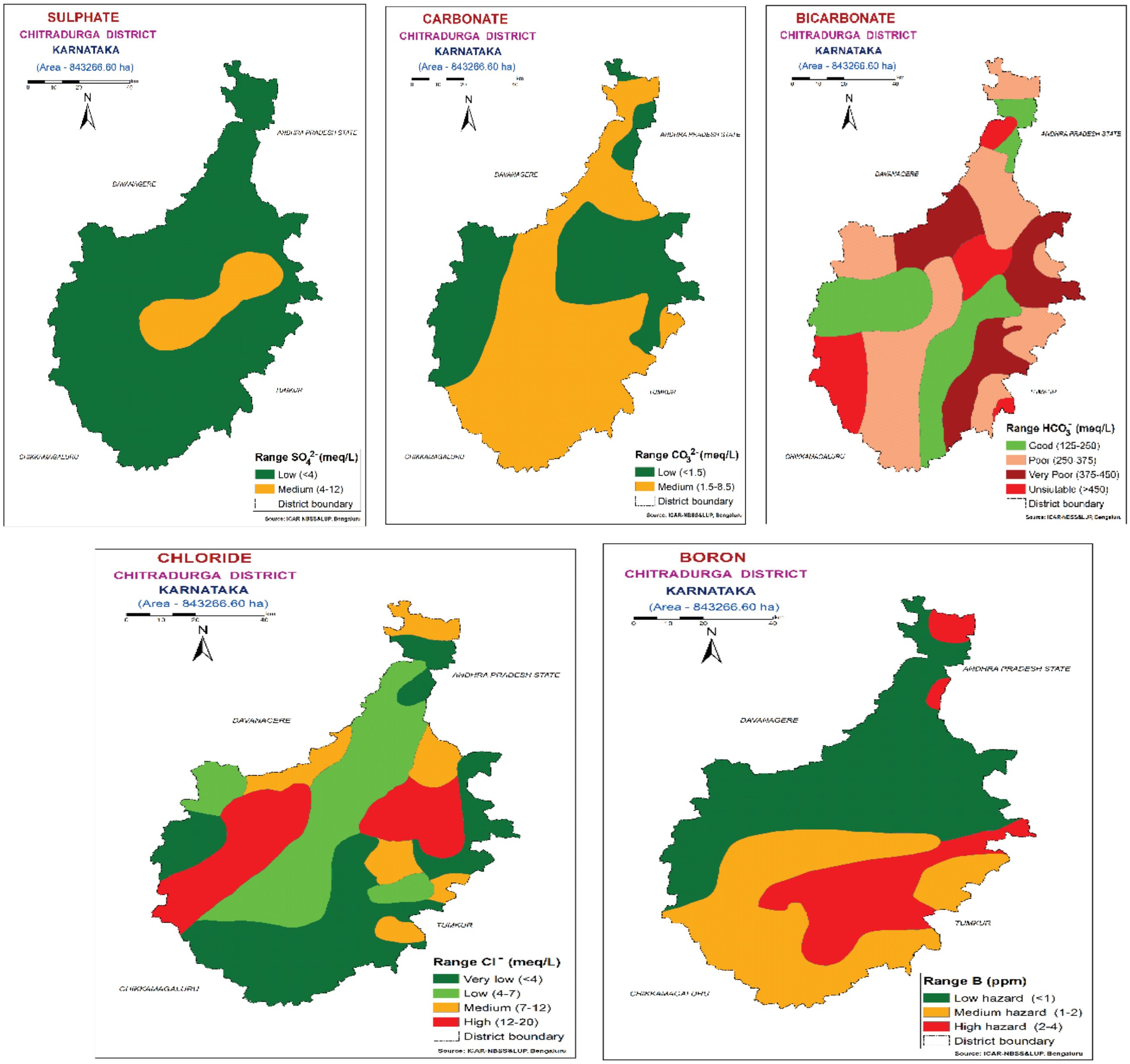


FIGURE 3 Geographical pattern of Chitradurga groundwater properties

TABLE 2 Descriptive statistics of groundwater parameters analysed

	pH	EC	Ca	Mg	K	Na	So_4	Co_3	HCO_3	CI	B
		(µS/cm)	------------mg l^{-1}------------								(ppm)
Min	7.49	764	1.31	17.14	0.34	41.50	6.08	18.00	134.20	78.10	0.05
Max	9.06	4400	55.23	135.32	79.25	790.80	134.40	90.00	500.20	795.20	3.83
Average	8.38	1599	10.43	50.69	4.46	205.08	43.31	51.16	340.49	216.23	1.34
SD	0.45	669	10.44	26.73	10.47	131.82	29.22	19.11	78.28	156.77	1.06

TABLE 3 Permissible limits for groundwater parameters for drinking purposes

Parameter	BIS (2012)	WHO (2004)	
		Most desirable	Max. allowable
pH	6.5-8.5	6.5	8.5
EC (µS/cm)	3000	1400	-
TDS (mg l^{-1})	2000	500	1500
TH (mg l^{-1})	600	100	500
Ca^{+2} (mg l^{-1})	200	75	200
Mg^{+2} (mg l^{-1})	100	50	150
Na^{+} (mg l^{-1})	200	-	200
K^{+}(mg l^{-1})	10	-	12
Cl^{-} (mg l^{-1})	1000	200	600
$SO4^{-2}$ (mg l^{-1})	200	200	400

3.2 | Original and Classification of groundwater of Chitradurga district

Piper diagrams indicate the cation and anion combinations that form triangles on a common baseline, which is used to classify groundwater types diagrammatically. The Piper diagram (*Fig. 5*) indicates that the groundwater is dominated by the Na^{+}- K^{+}- Cl^{-}- HCO_3^{-} type, the (Na^{+}-Ca^{2+}-Mg^{2+}- Cl^{-}- HCO_3^{-}) type, and the mixed type, which regularly accumulates residual carbonate in irrigation water. The Piper diagrams also show alkalis (Na^{+}+K^{+}) were higher than alkaline earth metals (Ca^{2+}+ Mg^{2+}), and Cl^{-} and HCO_3^{-} are the major anions found in groundwater that might be an occurrence of halite (NaCl), $NaHCO_3$, KCl, and $KHCO_3$ dissolution.

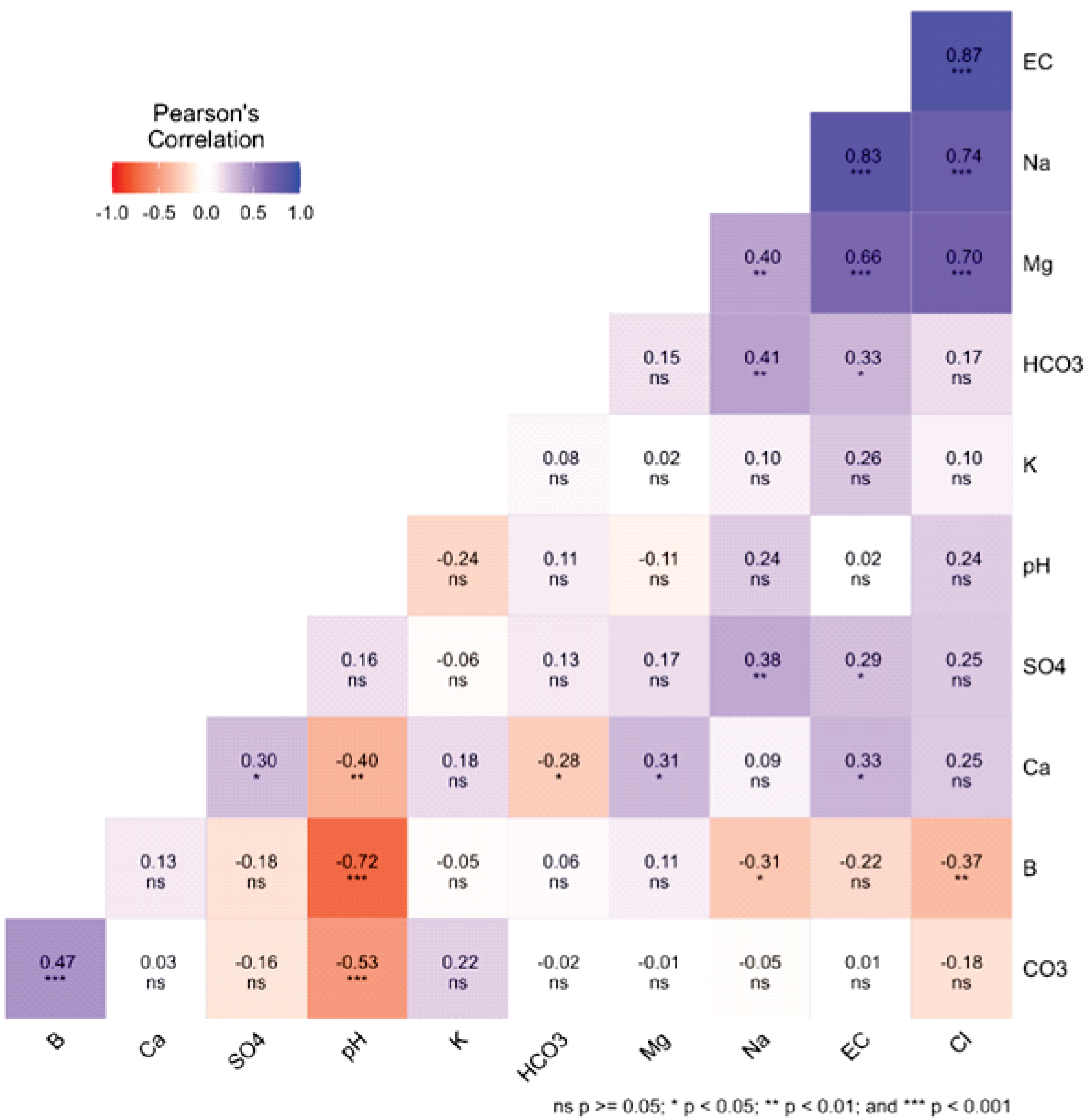


FIGURE 4 Association of groundwater parameters, Chitradurga district

A Gibbs diagram reveals the hydro-geochemical processes. The minerals influence water quality in the groundwater-aquifer system, which is helpful in understanding the genesis of groundwater. The Gibbs plot for cations (Na^+/(Na^+ + Ca^{2+}) and anions (Cl^- / Cl^- + HCO_3^-) (Fig. 6) directs that most of the cations in groundwater are of 'evaporation and mineral dissolution origin' and evaporation-crystallization dominance' and anions are of rock origin. In arid and semiarid regions, the elevated evaporative demand, combined with chemical weathering of rocks and human activities, contributes to an increase in total dissolved solids (TDS) in groundwater. This shift indicates a transition from rock dominance to the evaporation zone, potentially influenced by a higher concentration of sodium ions (Na^+) relative to chloride ions (Cl^-) in water samples, which may result from cation exchange processes or pollution from anthropogenic sources. The sulfate-to-chloride ratio (SO_4^{2-}/Cl^-), which exceeds 0.05 in all analyzed water samples, suggests the influence of agricultural return flow, indicating that the application of gypsum fertilizers and the dilution of gypsiferous minerals affect the mineral composition of the groundwater. In the Chitradurga district, the primary water-bearing formations include gneisses, fractured granitic gneisses, and hornblende schists (CGWB, 2013).

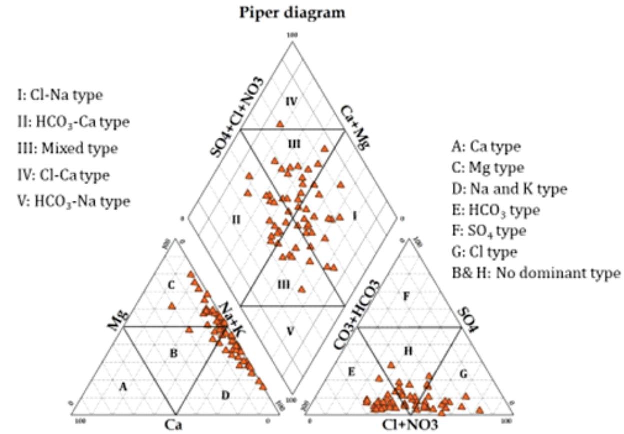


FIGURE 5 Piper diagram for the Groundwater's of Chitradurga district

Gibbs Diagram

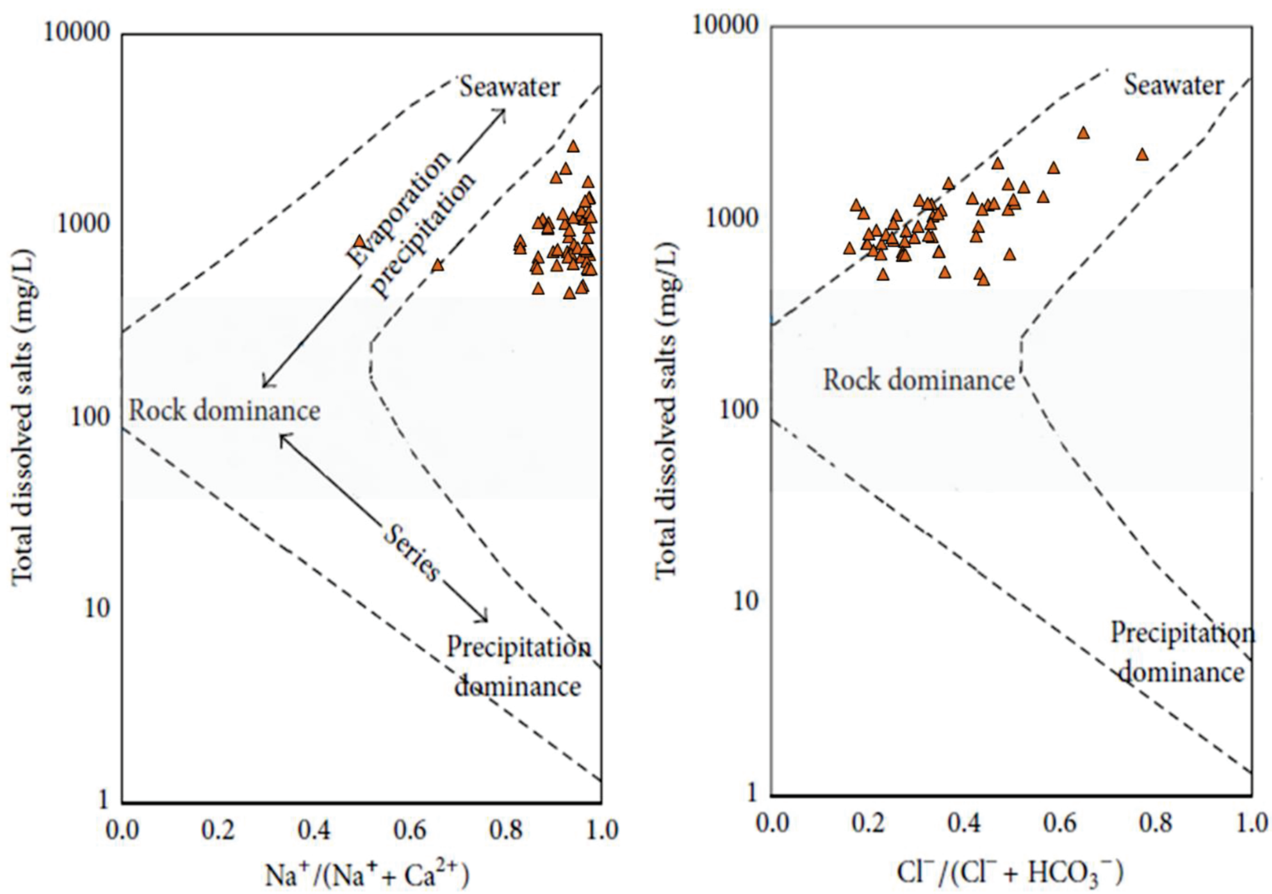


FIGURE 6 Gibbs diagram for the groundwaters of Chitradurga district

3.3 | Suitability of groundwater for drinking, Chitradurga district

The fitness of ground waters for drinking is evaluated using the water quality parameters *viz*., total hardness (TH), total dissolved solids (TDS), and water quality index (WQI), data presented in Table 4 and Fig. 7 show the spatial distribution of these parameters. The TH varied from 75.53 to 622.63 with a mean of 234.64, and the spatial distribution shows that more than 80% of the area has a high TH (>180 mg CaCO3 l_{-1}), indicating that the water is considered very hard. However, TH up to 600 mg $CaCO_3$ l^{-1} is suitable for consumption as per BIS maximum permissible limits (Sharma *et al.*, 2017). The water hardness may be due to the presence of carbonates and bicarbonates of alkaline earth metals, such as calcium and magnesium (Chaudhary & Satheesh kumar, 2018). The TDS varied from 488.96 to 2816.00, with a mean of 1023.49. The spatial distribution shows that it ranged from low to medium throughout the entire district. Higher TDS is directly related to the occurrence of elevated concentrations of soluble salts (Chaudhary & Satheeshkumar, 2018). TDS up to 1000 mg l^{-1} it fits for consumption, and up to 3000 mg l^{-1} is beneficial for irrigation (Sharma *et al.*, 2017). Thus, water can be used for drinking. However, the WQI ranged from 30 to 81, with a mean of 43, and the geographical pattern indicates that it is good to excellent in all the water samples in the district; thus, the Chitradurga groundwater is suitable for drinking. Since there were no major industries or municipalities, the groundwater has remained suitable for consumption and substantially unpolluted (Khatri *et al.,* 2020).

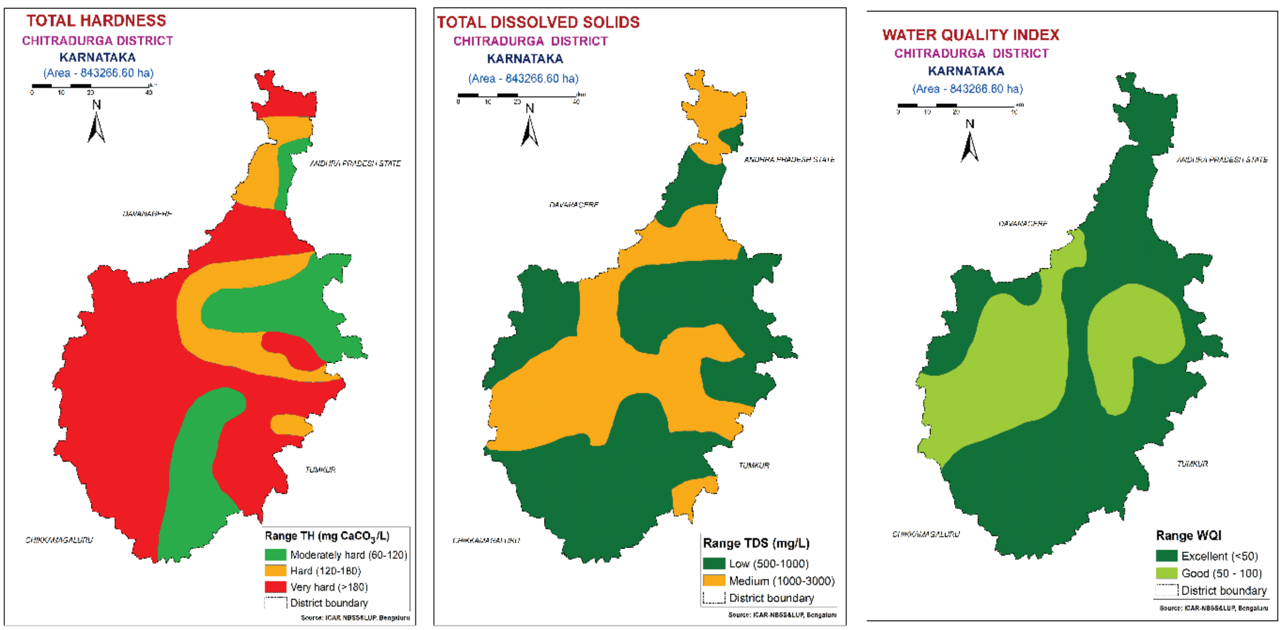


FIGURE 7 Geographical pattern of Chitradurga groundwater quality parameters for drinking suitability

3.4 | Irrigation suitability of groundwater for drinking, Chitradurga district

The major groundwater hydro-chemical quality parameters used to determine its suitability for irrigation (Table 4) are EC, soluble sodium % (SSP), sodium adsorption ratio (SAR), residual sodium carbonate (RSC), Kelly's ratio/Kelly's index (KI), permeability index (PI) and magnesium ratio/magnesium hazard (MH). The spatial distribution of these quality parameters is presented in Fig. 8. To determine the suitability of groundwater for irrigation, sodium concentration is a primary parameter to consider in the assessment because sodium-rich water, when irrigated, reacts with the soil and reduces its permeability. When sodium interacts with carbonate and chloride, it leads to alkaline and saline soils, respectively. Higher levels of Na^+ in irrigation water can affect soil texture and permeability; however, Na^+ concentrations in groundwater of up to 60 are regarded as permissible for agricultural purposes (Sharma *et al.*, 2014). Thus, the groundwater chemical quality was studied by plotting analytical EC data v/s sodium per cent, i.e., Wilcox diagram (*Fig. 9*) shows that 50% of water samples belong to good to permissible, 40% falling under permissible-doubtful, six samples under doubtful-unsuitable, and three samples were unsuitable. Doubtful and unsuitable samples require proper treatment before irrigation, as these samples, when irrigated without treatment, may cause alkali and saline soils, thereby hindering crop production and productivity, as well as deteriorating soil health. The SAR ranged from 1.31 to 19.14 with a mean of 6.13. The U.S. Salinity Laboratory uses the Wilcox log diagram to plot electrical conductivity (EC) versus SAR, which classifies groundwater as CnSn, i.e., a pair of EC (C1-C4) and SAR (S1-S4) classes. Here, EC is referred to as a salinity threat, whereas SAR is considered an alkalinity threat. Wilcox's log diagram (*Fig. 9*) shows that 89% (49 samples) of the water samples belonging to C3S1 indicate high salinity and low Na, which requires drainage and is otherwise dangerous. However, 11

% (6 samples) of waters falling under C4S1 indicate very high salinity and low sodium, which cause salinity problems to soils upon irrigation. However, cotton or millets can tolerate slight salinity, while sensitive crops could be harmed by 'doubtful' water; hence, salt-tolerant crops can be grown in these areas. And also this water requires prior treatment, along with the provided drainage. Higher concentrations of salts (high EC) in irrigation water result in the creation of saline soil. Salinisation is a major threat to irrigated lands, causing a loss of production as it limits crop growth by adversely affecting germination and yields, and also affects the choice of crops. The US Salinity Laboratories Riverside diagram (*Fig. 10*) also shows that low sodium but high salts, except one sample, which recorded SAR >19, indicating potential salinity and sodicity issues, as hard-rock aquifers often yield saltier water with low sodium relative to calcium/magnesium, resulting in low SAR. Thus, water samples are too salty to irrigate if irrigated without proper drainage, which may cause soil salinisation, which needs proper drainage in soils and also requires cultivating salt-resistant crops. The salinity present in groundwater is a result of the weathering of rocks, along with the process of evapotranspiration, which releases soluble salts into the groundwater. These salts primarily consist of calcium, sodium, and magnesium chlorides, as well as bicarbonates, sulfates, and carbonates. The study found that the spatial distribution of SAR was good to excellent, and it is within the permissible limit (<26).

TABLE 4 Statistical analysis of parameters for assessing groundwater quality

	TDS ($mg\ l^{-1}$)	SSP (%)	SAR	RSC	TH	KI	PI	MH	PS	WQI
Min	488.96	25.60	1.31	7.10	75.53	0.34	20.41	59.99	2.96	30
Max	2816.00	90.67	19.14	8.63	622.63	9.72	43.36	98.65	23.45	81
Average	1023.49	63.07	6.13	2.58	234.64	2.26	29.21	89.14	7.19	43
SD	428.17	14.37	3.67	2.72	120.76	1.71	4.51	8.67	4.52	10

Higher RSC in water causes the adsorption of higher sodium in the soil. The RSC ranged from -7.10 to 8.63 with a mean of 2.58. The geographical pattern of RSC was medium to bad in more than 66% of the area. Thus, 66% (36 samples) of groundwaters are not suitable for irrigation as these waters have more (CO_3^{2-} + HCO_3^{-1}) compared to alkaline earth metals (Ca^{2+}+Mg^{2+}), thus leading to complete precipitation of Ca^{2+} and Mg^{2+} and deposits residual carbonate in the soil upon irrigation, resulting in alkali build-up. The high amount of calcareous rocks may be the reason for the alkalinity of waters in the district (Nagaraju *et al.,* 2014). The PI is affected by Ca^{2+}, Mg^{2+}, Na^{+}, Cl^{-1}, and HCO_3^{-1} values in the soil, and it recorded 20.41 to 43.36 with a mean of 29.21. The geographical pattern of PI indicates that 78% (43 samples) of the samples have good permeability, and around 22% (12 samples) of the waters are unsuitable. A magnesium ratio of > 50 causes soil alkalinity/sodicity in soils due to a high concentration of Mg^{2+}, as it behaves like Na^{+} and causes soil structure deterioration by dispersing clay content, particularly in irrigated lands/lowlands. The MH varied from 59.99 to 98.65 with a mean of 89.14 (SD: 8.67). The geographical pattern of MH shows that the entire Chitradurga district groundwater is found to be magnesium-hazardous, thus leading to alkalinity/sodicity upon irrigation. Consequently, 100% of the water samples are injurious and unsuitable for irrigation use. Higher magnesium levels in groundwater may be contributed by the dolomite source in the district (Nagaraju *et al.,* 2014).

Similarly, KI shows higher concentrations of sodium in water; when KI > 1, the water is unsuitable. The recorded concentrations ranged from 0.34 to 9.72, with a mean of 2.26. The spatial distribution of KI indicates that the Chitradurga ground waters were found to be non-permissible in around 86 % of water samples, as it recorded KI of >1. The SSP varied from 25.60 to 90.67% with a mean of 63.07%. The spatial distribution of SSP was found to be fair to poor in around 93 % (51 samples) of water samples, as higher sodium has the potential to react with the soil upon irrigation and leads to a reduction in soil permeability through the formation of sodium hazard in soil. The higher percent of soluble sodium might be due to the minerals sodium and potassium feldspar in this region, weathering and dissolution of these minerals and also addition of chemical fertilizers resulted higher levels of sodium and potassium contents in the groundwater (Chandrakala *et al.*, 2024) and also the phenomena of cation interaction and exchange between Ca^{2+} and Na^{+} also occurs naturally in the ground water (Chaudhary & Satheesh kumar, 2018).

Potential salinity indicates that groundwater containing salts with low solubility precipitate in the soil upon irrigation and accumulate in the soil itself. In contrast, the salts with higher solubility have the potential to cause soil salinity (Doneen, 1964b; Siamak & Srikantaswamy, 2009). Chitradurga groundwaters recorded PS of medium to high in more than 64 per cent (35 samples) of samples, thus may lead to soil salinity upon irrigation. The elevated concentration of salts negatively impact plant and crop growth by weakening plant stems and clogging soil pores (Singh *et al.,* 2024) Hwang *et al.* (2017) reported similar studies on assessing groundwater quality for irrigation suitability in Korea. Weathering processes affecting rocks, the return flow associated with agriculture, and the pronounced evaporation-precipitation of seawater

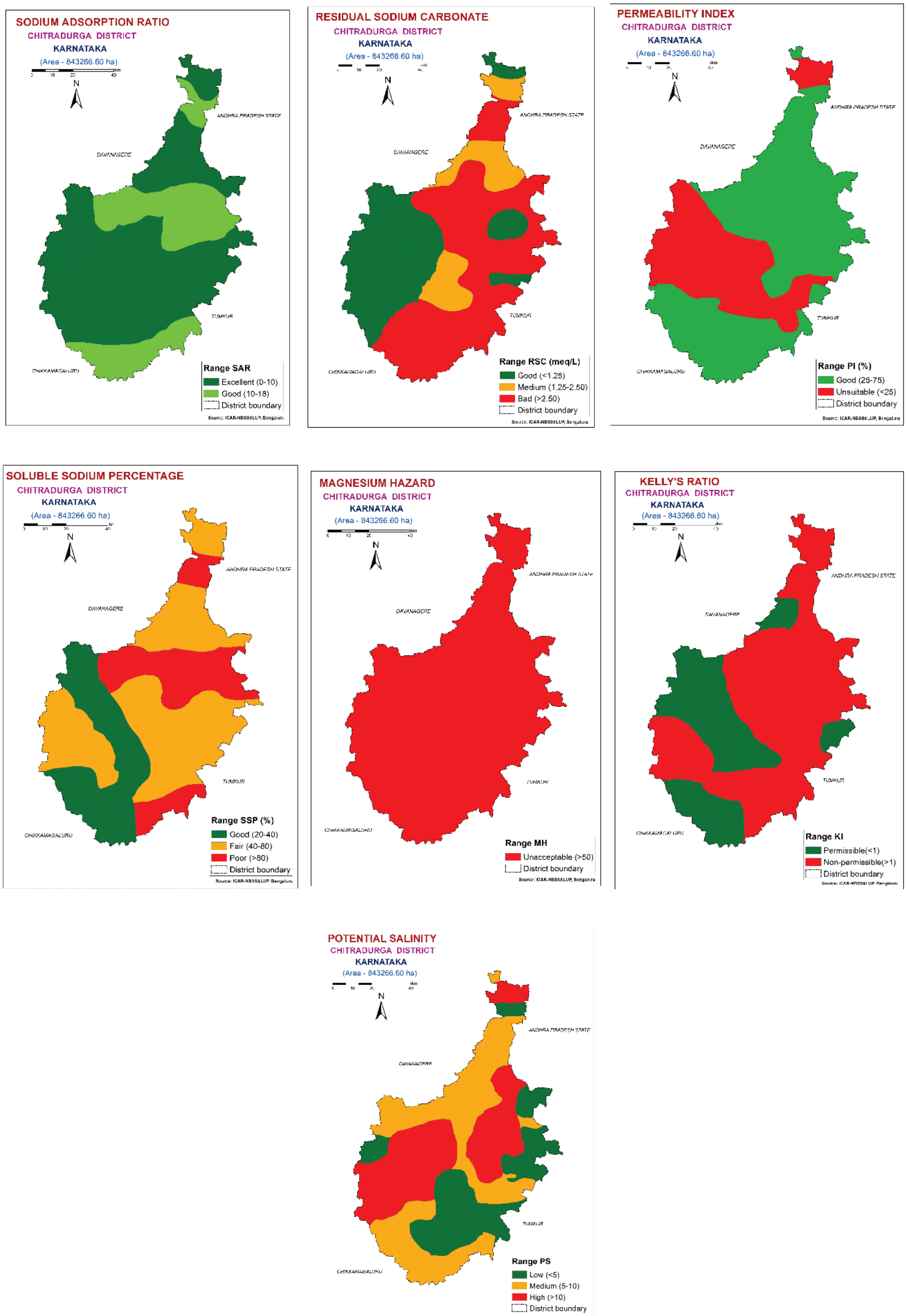


FIGURE 8 Spatial distribution of Chitradurga groundwater quality parameters for irrigation suitability

in arid zones are vital elements that contribute to higher levels of major anion and cation concentration, which makes the groundwater unsuitable for irrigation. Additionally, due to low rainfall, as the Chitradurga district is a drought-prone area, there was a low recharge of the aquifer, resulting in deterioration of groundwater quality.

Pesticide contamination and anthropogenic activities are also significant issues affecting groundwater quality in the district. Artificial recharge to groundwater through percolation tanks, check dams, and nalla bunds is the most effective solution to improve groundwater quality and reduce contamination, as it can dilute the groundwater with high-quality canal waters in the plain areas of the district (CGWB, 2013). And also strategies such as rainwater harvesting to dilute salts, crop rotation with salt-tolerant crops, or blending groundwater with canal water are recommended. Few methods for groundwater treatment include salinity reduction and removal of contaminants through adsorption and electrochemical techniques, as well as dilution of the contaminated water source with rainwater (Khatri *et al*., 2020; Gupta & Misra, 2016). Implementing best land use practices and optimum use of agricultural inputs can also help mitigate groundwater quality issues (Gupta., 2024)

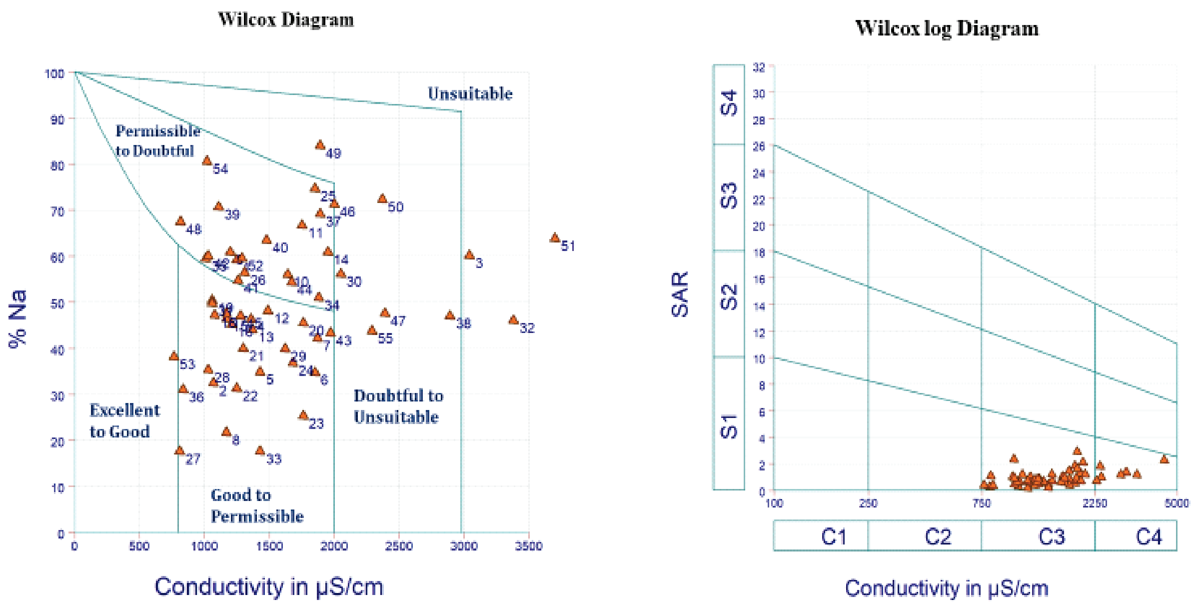


FIGURE 9 Wilcox and Wilcox log diagrams for the ground waters of Chitradurga district

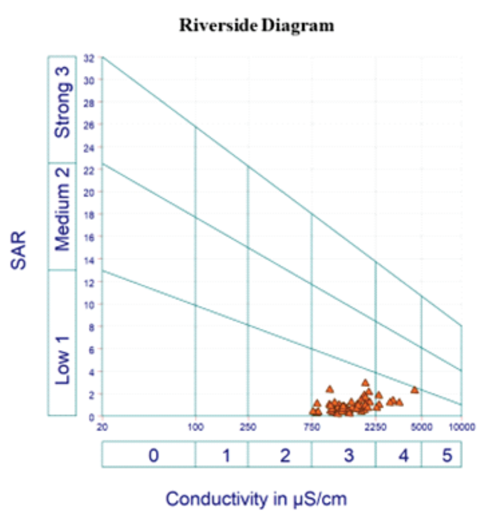


FIGURE 10 Riverside diagram for the ground waters of Chitradurga district

4 | CONCLUSIONS

This comprehensive assessment of 55 groundwater samples from Chitradurga district revealed Na^{+}-K^{+}-Cl^{-}-HCO_3^{-} dominated hydrochemistry, primarily originating from rock weathering processes and evaporation-precipitation mechanisms typical of semi-arid environments. The Piper diagram classification identified mixed cation-anion types with alkalis (Na^{+}+K^{+}) exceeding alkaline earth metals (Ca^{2+}+Mg^{2+}), indicating significant mineral dissolution and cation exchange processes. Water Quality Index (WQI) analysis demonstrated that 87% of groundwater samples (WQI: 30-50) meet excellent standards for potable use, while 13% fall within good quality range (WQI: 51-81). Total hardness values (75.53-622.63 mgl_{-1} $CaCO_3$) remained within BIS permissible limits, and total dissolved solids (488.96-2,816 $mg\,l_{-1}$) indicated generally acceptable quality for consumption, despite elevated salinity in localized areas.

Critical irrigation quality parameters revealed 70% of samples classified as C3S1 (high salinity, low sodium) and C4S1 (very high salinity, low sodium), requiring drainage management, and 100% of samples demonstrated Magnesium Hazard (MH) values >50%, indicating universal risk of soil structure deterioration and alkalinity development. Geographic analysis revealed distinct contamination zones with higher sodium and potassium concentrations in northern arid regions, likely attributed to enhanced evaporation rates and deeper groundwater extraction. Boron concentrations were elevated in southern semi-arid areas due to sequential solute deposition processes. These findings provide essential baseline data for developing targeted groundwater management strategies in drought-prone semi-arid regions. The spatial distribution maps enable precision interventions for specific taluks, optimising resource allocation for water treatment infrastructure.

The irrigation suitability assessment offers critical guidance for crop selection and irrigation scheduling. Farmers can implement appropriate soil amendments (gypsum application, organic matter incorporation) and adopt salt-tolerant crop varieties in areas with high salinity groundwater. Results support evidence-based policy decisions for sustainable groundwater utilization, including mandatory water treatment protocols for irrigation in 70% of the study area and artificial recharge programs to dilute contaminated aquifers.

Nevertheless, the current analysis represents only pre-monsoon conditions (February-March 2023-2024). Comprehensive seasonal monitoring across monsoon and post-monsoon periods is essential to understand temporal hydrochemical fluctuations and establish dynamic management protocols. While natural processes dominate groundwater chemistry, anthropogenic contributions from agricultural fertilizers, industrial activities, and urban waste require detailed source apportionment studies using isotopic analysis and multivariate statistical techniques.

Further research is required to identify cost-effective treatments for chemical signatures such as high Na^+, Mg^{2+}, and HCO_3^-. Urgent pilot studies on ion exchange, reverse osmosis, and biological systems in local conditions are needed. Long-term monitoring incorporating climate data is vital to understanding how rainfall and temperature influence groundwater, especially in drought-prone areas. Although limited, field experiments assessing water quality impacts on soil and crops are essential for validation and improved management. The lack of comprehensive cost-benefit analyses restricts adoption by resource-limited farmers. Creating decision support systems that utilize real-time water, weather, and crop data represents a top research priority.

Based on these findings, immediate interventions should include: (1) implementation of artificial recharge programs using canal water to dilute contaminated aquifers, (2) mandatory water treatment for irrigation in high-risk zones, (3) promotion of salt-tolerant crop varieties and deficit irrigation techniques, and (4) establishment of continuous water quality monitoring networks to track remediation effectiveness and prevent further deterioration. These measures, combined with targeted research addressing identified gaps, will ensure sustainable groundwater utilization while maintaining agricultural productivity and soil health in Chitradurga district.

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CONFLICT OF INTEREST

There are no conflicts of interest

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DATA AVAILABILITY STATEMENT

Data is available with the corresponding author and will be provided if its required

AUTHOR'S CONTRIBUTION

CM is the principal investigator who conducted the investigation and wrote the manuscript, RC accompanied the PI during sample collection in the field and prepared the figures and graphs. GAT checked the manuscript for plagiarism using turnit in software and edited the plagiarized contents , SGC reviewed the draft manuscript, PS done the laboratory water analysis, HR and PMV prepared the maps in GIS and and RV co-ordinated the work.

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