



RESEARCH ARTICLE

Impact of irrigation water quality on grain yield, chlorophyll content and ionic accumulation in paddy

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Abstract

In semi-arid regions, where groundwater serves as the primary source of irrigation, its quality plays a crucial role in sustaining soil health and agricultural productivity. This study assessed the groundwater quality and its effect on paddy crop performance in Hanumakonda district of Telangana state, India, through an integrated hydro chemical, spatial and crop response integrated approach. During the post-monsoon season (2024–25), A total of 78 groundwater samples were collected from 78 different locations across the study area and analysed for various parameters including pH, electrical conductivity (EC), major cations (Ca^{2+} , Mg^{2+} , Na^+ , K^+), anions (CO_3^{2-} , HCO_3^- , Cl^- , SO_4^{2-}), sodium adsorption ratio (SAR), residual sodium carbonate (RSC) and boron (B). The dominant cations and anions followed the order $\text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+ > \text{Na}^+$ and $\text{Cl}^- > \text{SO}_4^{2-} > \text{HCO}_3^- > \text{CO}_3^{2-}$, respectively. Based on CSSRI classification 48 % of samples were suitable for irrigation and the rest showed salinity and alkalinity hazards. Strong negative correlation between EC and grain yield ($r = -0.94^{**}$) and between EC and SPAD ($r = -0.90^{**}$) was found and at the same time a strong positive correlation between grain yield and SPAD ($r = 0.95^{**}$) was obtained, while a strong negative correlation between grain yield and leaf sodium ($r = -0.97^{**}$) was also obtained. Groundwater quality was mapped using GIS and spatial variability was identified. The findings provide valuable insights for sustainable groundwater management and irrigation planning in semi-arid agroecosystems.

Keywords: grain yield; groundwater quality; salinity; sodium adsorption ratio; spatial variability

Introduction

Water quality plays a critical role in irrigation, influencing soil health and agricultural productivity, particularly in semi-arid regions where groundwater is the primary irrigation source. Irrigation water suitability is largely dependent on salinity, sodicity and ionic composition which directly impact soil physicochemical properties and plant growth (1). Water quality varies significantly with rock-water interactions and mineral weathering, ion exchange processes in the aquifers, etc., resulting in a significant spatial variation of water quality (2–4).

However, in water-scarce regions, the increasing exploitation of groundwater resources has raised significant concerns regarding groundwater quality and long-term sustainability. Insufficient quality of irrigation water may cause salinity and sodicity stress in the soil, leading to a decrease in soil permeability, imbalance of nutrient levels and ultimately a decrease in crop yields (5–8). High electrical conductivity (EC) causes osmotic stress and high sodium adsorption ratio (SAR) results in degradation of soil structure. Furthermore, the excessive accumulation of sodium (Na^+) and chloride (Cl^-) ions in plant tissues negatively impact on physiological functions such as chlorophyll biosynthesis and photosynthesis, thereby decreasing crop production (9–12). The use of a hydrochemical approach along with Geographic Information Systems (GIS) has been increasingly

used in recent years to understand the spatial variability of groundwater quality (13–15). These studies have helped to gain better knowledge on groundwater suitability for irrigation and helped identify critical areas under salinity and alkalinity hazards. Most of the previous studies, however, are descriptive in nature and show only classification of water quality with less emphasis on the relationship of hydrochemical parameters with crop physiology and production under field conditions. Although groundwater quality assessment has made progress, few studies have taken an integrated approach to quantitatively connecting water quality parameters to plant physiological traits (e.g., chlorophyll content, ion accumulation) and crop productivity (16). Several studies have reported that irrigation water with elevated EC, SAR, residual sodium carbonate (RSC) and chloride concentrations negatively affects rice growth, nutrient uptake, photosynthetic efficiency and grain yield through osmotic stress, ion toxicity and soil degradation processes. Saline and sodic irrigation conditions often promote excessive accumulation of Na^+ and Cl^- ions in plant tissues, disrupting ionic homeostasis, increasing the Na^+/K^+ ratio, reducing chlorophyll synthesis and impairing physiological processes essential for crop growth and productivity. Although previous research has extensively examined the individual effects of irrigation water salinity on soil properties, crop yield, chlorophyll content, or plant ion balance, a comprehensive evaluation linking irrigation water quality

indices directly with leaf chlorophyll status, ionic composition and grain yield remains limited (17–19). Consequently, the present study advances current understanding by integrating EC, SAR, RSC and chloride concentrations with SPAD-based chlorophyll measurements, leaf ionic composition and paddy grain yield, thereby elucidating the physiological and ionic pathways through which groundwater quality influences rice productivity under field conditions. This integrated approach provides valuable insights for developing sustainable irrigation management strategies in regions affected by groundwater quality constraints. The groundwater is heavily exploited for agriculture in Hanumakonda district of Telangana, India, which is a semi-arid agro-ecosystem where limited and variable rainfall makes groundwater the primary source of irrigation. The relationships between the spatial variability of groundwater quality and crop performance have not been fully investigated, although localised information on groundwater quality has been reported.

The objectives of this study were to assess groundwater quality for irrigation based on certain hydrochemical parameters, analyse the spatial variation of groundwater quality through GIS techniques and evaluate the relation between the hydrochemical parameters of the irrigation water and paddy crop performance in terms of grain yield, SPAD values and ionic composition of leaves. The results will help to inform groundwater use in a sustainable way and offer practical solutions to manage the negative impacts of poor-quality irrigation water.

Materials and Methods

Study area

Hanumakonda district in Telangana, India is in the eastern part of the state with a geographical area of 1312.02 km². It lies between 16°15'0" to 17°45'0" N latitude and 79°15'0" to 79°45'0" E longitude (Fig. 1). The district is bordered by Jayashankar Bhupalpally and Karimnagar Districts to the North and North East; Mulugu (to the east) and Siddipet (to the northwest); Jangaon (southwest) and Warangal (southeast). The study area is in Godavari and Krishna river basins (20).

Climate and rainfall

The district's climate is semi-arid with hot summers and relatively cool winters. The study area experiences annual temperature extremes ranging from 5.6 to 47.6 °C. The average rainfall in a year is roughly 889.5 mm with over 80 % of the total coming during southwest monsoon (June–September) and the rest during the northeast monsoon (October–November) (21,22).

Geomorphology, soils and geology

The district has undulating topography with its hills, valleys and plain. Pediplains dominate the landscape (≈ 93 %), while pediments (≈ 5 %) and structural hills (≈ 1 %) are less common physiographic units. Most of the soils are loamy (63 %) and clayey (36 %) with a high percentage of fine mixed and montmorillonitic soils. Geologically, granitic rocks underlie 98 % of the area and gneiss of Archean to Proterozoic age underlie 2 % of the area (21, 22).

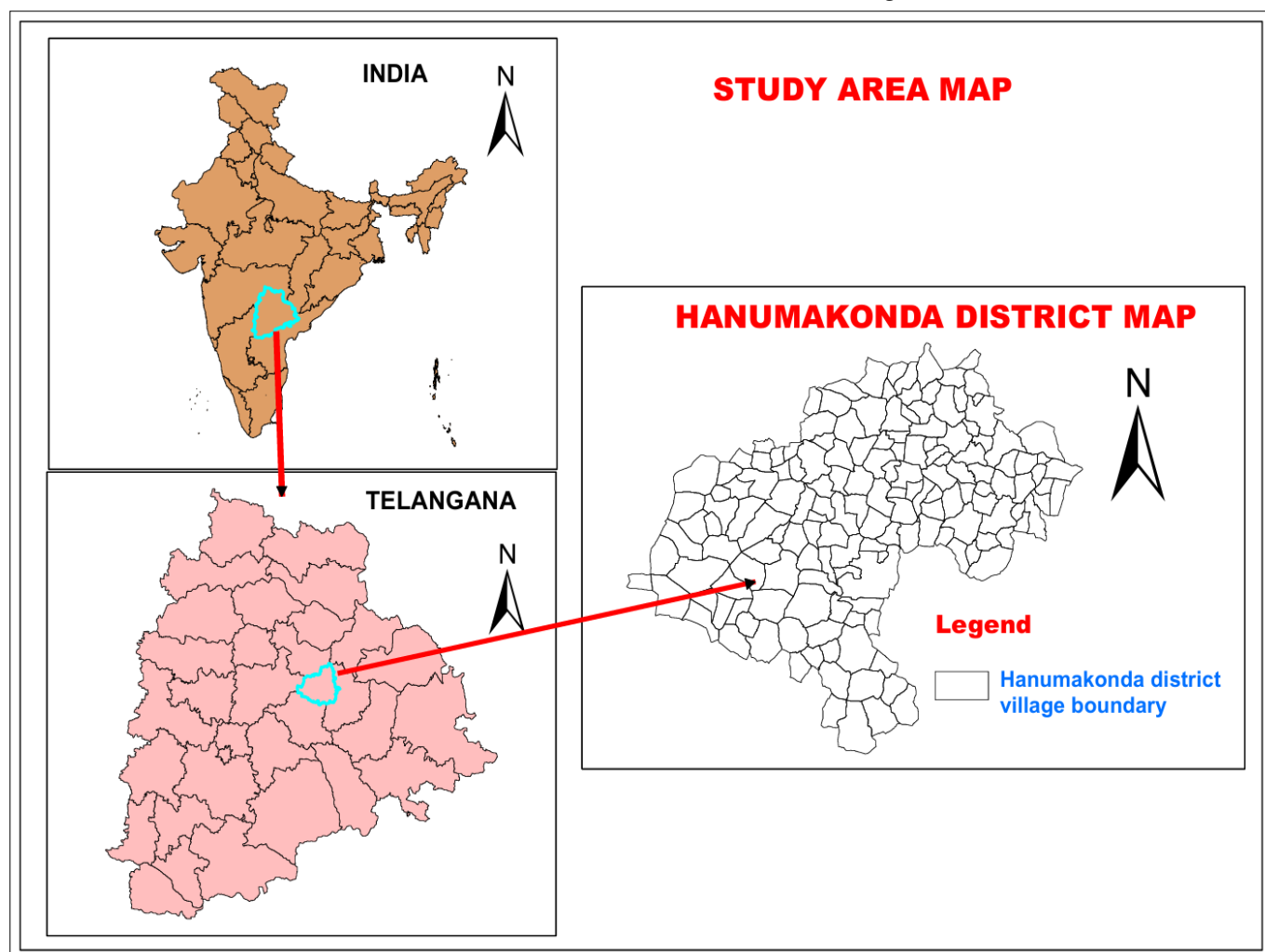


Fig. 1. Location map of the study area in Hanumakonda District, Telangana, India.

Source: ArcGIS software.

Groundwater resources

The district has 31143 irrigation wells (24145 dug and 6998 tube) that irrigate around 86.37 % of the cultivated area. Net annual groundwater availability is 189.62 MCM, overall groundwater development stage is estimated to be approximately 62 % (21, 22).

Collection of water samples and analysis

The post-monsoon samples of groundwater (2024–25) were collected using a stratified random sampling method, resulting in a total of 78 samples. The representative samples were collected from each mandal with geographical coordinates (Fig. 2), 2–3 samples from each mandal. Each samples were collected in three pre-cleaned polyethylene bottles with three rinses of the sample water. Water from open wells was drawn by rope and bucket while tube well samples were drawn after pumping the water for 5–6 min to ensure that the sample was representative. Microbial alteration was prevented by adding a few drops of toluene immediately after collection. The sample of water was analysed according to standard method (23, 24). The pH was measured using the digital pH meter and EC was obtained by the conductivity bridge (25). The estimation of chloride was done by Mohr's method and that of carbonate and bicarbonate by double-indicator method. The Versenate (EDTA titration) method was used to determine calcium and magnesium (26). A flame photometer was used to determine the concentration of sodium and potassium (25). Chloride (Cl⁻) was estimated by the Mohr's titration method using silver nitrate as the titrant and potassium chromate as the indicator following standard procedures. Boron concentration was determined colorimetrically

using the Azomethine-H method and the absorbance was measured at 420 nm using a UV-Visible spectrophotometer (27). All ionic concentrations were expressed in milliequivalents per litre (meq L⁻¹), except chloride and boron which were expressed in mg L⁻¹. Standard equations 1 and 2 are used to calculate the RSC and SAR (27):

$$\text{RSC} = [(\text{CO}_3^{2-} + \text{HCO}_3^-) - (\text{Ca}^{2+} + \text{Mg}^{2+})] \quad \text{Eq. 1}$$

$$\text{SAR} = \text{Na}^+ / \sqrt{[(\text{Ca}^{2+} + \text{Mg}^{2+})/2]} \quad \text{Eq. 2}$$

Crop data collection

Relationships between irrigation water quality and crop performance were established by taking paddy crop data (grain yield, chlorophyll content, Na and Cl content in plant) from fields irrigated using the respective groundwater sources. Plant samples were collected from the same fields from which groundwater samples were obtained, ensuring a direct linkage between irrigation water quality and crop response. The predominant rice variety cultivated in the study area was RNR 15048 (Telangana Sona). Farmers applied the recommended fertiliser dose of 120 : 60 : 40 kg N₂O₅ ha⁻¹, maintained standard crop spacing (15 cm between hills and rows) and adopted conventional flooded irrigation using groundwater as the primary source of irrigation. Representative areas were harvested and grain yield (t ha⁻¹) recorded. The active vegetative stage was used for chlorophyll content measurement with SPAD meter. Samples of leaves were taken, oven dried and analysed for the concentration of sodium (Na⁺) and chloride (Cl⁻) as per standard lab procedures (25, 26).

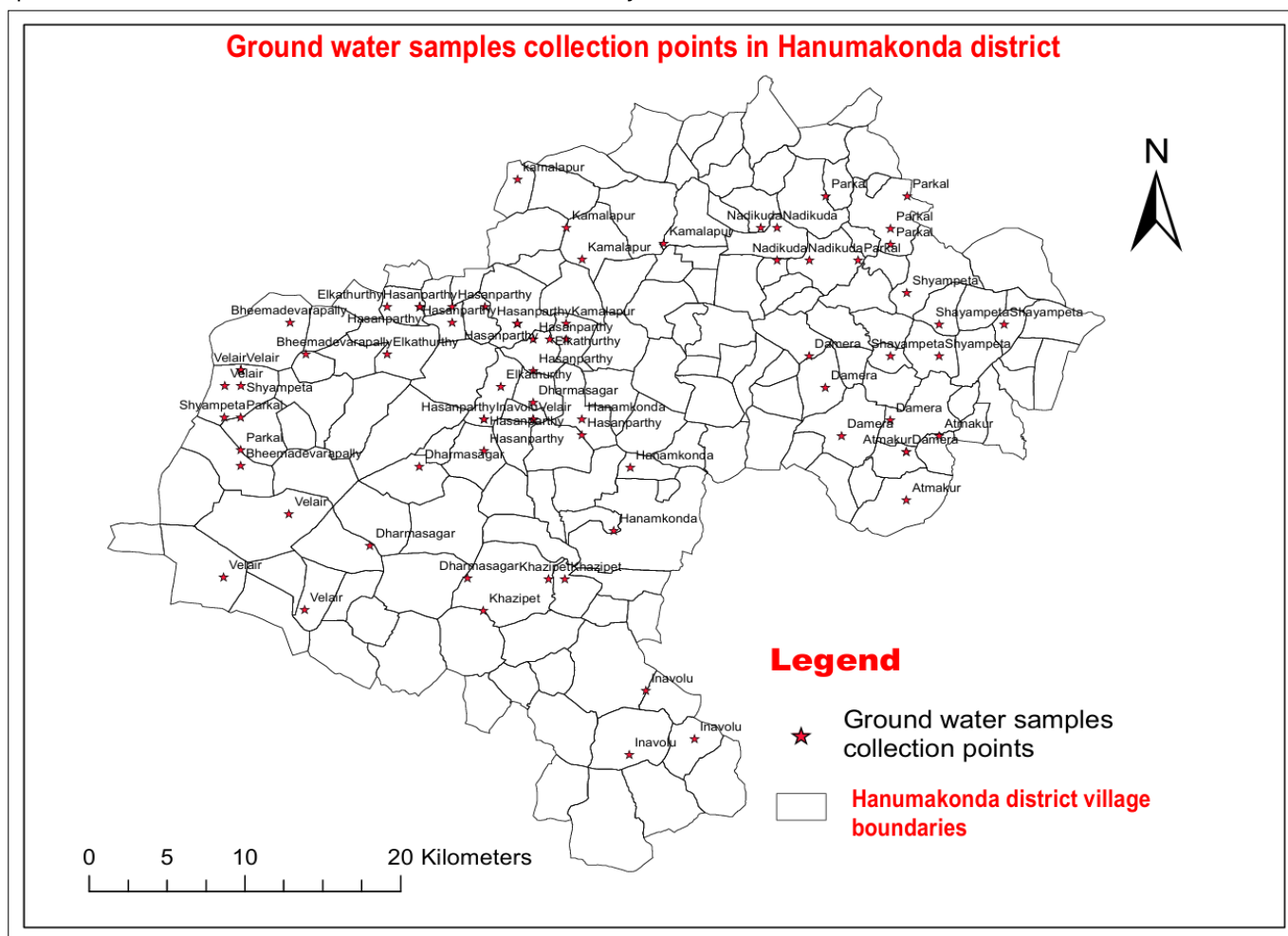


Fig. 2. Groundwater samples collection points in study area.

Source: ArcGIS software.

Water quality classification

The groundwater suitability for irrigation was determined after considering the EC, SAR and RSC criteria as per Central Soil Salinity Research Institute, (CSSRI), Karnal (25–27).

Spatial and statistical analysis

A handheld GPS with a precision of 3–5 m was used to take geographical coordinates. The ordinary kriging technique was used to produce spatial distribution maps of groundwater quality parameters in ArcGIS (10.6 version). Descriptive statistical analysis was carried out including mean, range, standard deviation and coefficient of variation were computed according to standard procedures. The SPSS software was used for Pearson's correlation analysis of water quality parameters, SPAD values, leaf ionic composition and paddy grain yield to assess the correlation among them. Significance levels of $p \leq 0.05$ and $p \leq 0.01$ were used to test statistical significance (28–30).

Results and Discussion

Groundwater quality determination

Groundwater quality will depend on the concentrations of dissolved constituents in the groundwater. Various chemical parameters including pH, EC, cations (Ca^{2+} , Mg^{2+} , Na^+ and K^+) and anions (CO_3^{2-} , HCO_3^- , Cl^- and SO_4^{2-}) were measured in the samples. The analytical results were subsequently used to calculate the residual RSC and SAR. Table 1 shows the descriptive statistics of analytical data of chemical parameters of groundwater samples collected during 2024–25 from various mandals of the Hanumakonda district, Telangana.

Water pH

Groundwater samples from Hanumakonda district had a pH range of 6.51 to 8.72 with a mean pH of 7.86, a CV of 8.0 % and a standard deviation of 0.59, which suggests that there is low variation among the samples (Table 1). The observed pH values were largely within the recommended range of 6.5–8.4 for irrigation water, indicating that the groundwater is generally suitable for agricultural use. Irrigation water with pH values outside this range may lead to nutrient imbalances, reduced nutrient availability and potential toxicity issues in soils and crops. The recommended pH range for irrigation water is 6.50–8.40, in which most crops grow well (31, 32). The lowest pH (6.51) was found in Peddapur village of Atmakur mandal and the highest pH (8.72) was found in Velair village of Velair mandal. The higher pH in some areas may be due to the presence of higher concentrations of the cations (Na^+ , Ca^{2+} , Mg^{2+}) and anions (CO_3^{2-} , HCO_3^-). Elevated pH values are commonly associated with the presence of carbonate and bicarbonate ions, as well as higher concentrations of sodium, calcium and magnesium derived from water-rock interactions and mineral weathering processes. In semi-arid regions, prolonged evaporation and dissolution of carbonate-bearing minerals can further increase groundwater alkalinity (33–35).

The spatial distribution of pH revealed that moderate alkaline (7.80–8.50) was prevailing in parts of Hanumakonda and Hasanparthy mandals and strongly alkaline ($\text{pH} > 8.50$) in Bheemadevarapally and Kamalapur mandals (Fig. 3) (36–38). The occurrence of alkaline groundwater in these areas may indicate enhanced carbonate weathering, higher bicarbonate concentrations and localised hydrogeochemical processes. Groundwater with pH values exceeding 8.5 may adversely affect nutrient availability, particularly micronutrients such as iron, zinc, manganese and copper, thereby influencing crop productivity if used continuously for irrigation (33–35). Out of the 78 groundwater samples analysed, 20.51 % were classified as neutral, 25.74 % as slightly alkaline, 33.33 % as moderately alkaline and 20.51 % as strongly alkaline (Table 2).

Table 2. Classification of groundwater samples based on pH in Hanumakonda District, Telangana

Sl. No	pH class	Number of samples	Percentage of samples
1	Neutral (6.50–7.30)	16	20.51
2	Slightly alkaline (7.30–7.80)	20	25.74
3	Moderately alkaline (7.80–8.50)	26	33.33
4	Strongly alkaline (> 8.50)	16	20.51

Water salinity (EC dS m⁻¹)

The EC was used for determining the water salinity. Results showed that the EC varied from 0.25 to 4.59 dS m⁻¹ with a mean value of 1.77 dS m⁻¹, a standard deviation of 1.31 and a coefficient of variation (CV) of 73.96 %, which were high (Table 1). The EC is frequently used to indicate the overall concentration of dissolved ions in water and is closely related to total dissolved solids (39). These dissolved components are derived from the natural hydrogeochemical processes and the geological formations (40, 41). The spatial distribution of EC (Fig. 4) revealed higher concentration (> 4.0 dS m⁻¹) in some areas of Velair and Kamalapur mandals. The groundwater samples were categorised into EC classes up to 6 dS m⁻¹ (Table 3). Among the 78 samples analysed, 64.10 % (50 samples) had $\text{EC} < 2.0$ dS m⁻¹, 23.08 % (18 samples) ranged between 2.0–4.0 dS m⁻¹ and 12.82 % (10 samples) fell within 4.0–6.0 dS m⁻¹. Only a few samples exhibited higher EC values. Madipally village of Hasanparthy mandal showed the highest EC (4.59 dS m⁻¹) which may be attributed to the clayey and montmorillonitic soils found in this area which can have a negative influence on drainage and salt buildup (42, 43). However, in contrast to this, the lowest EC (0.25 dS m⁻¹) was found in Parkal mandal, which is possibly due to the presence of coarse loamy soil in this mandal with good natural drainage, which can reduce the groundwater salinity. The differences in EC can be due to variation in hydrometeorology, topography, lithology, drainage, hydrogeology, weathering processes, surface water irrigation and over-exploitation of groundwater (44). The cation dominance was found to be in the following order $\text{Na}^+ > \text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+$. Major sources

Table 1. Descriptive statistics of groundwater chemical parameters in Hanumakonda District, Telangana

Sl. No	Water quality parameter	Range	Mean	Standard deviation	Coefficient of variation (CV) (%)
1	pH	6.51–8.72	7.86	0.59	7.52
2	Electrical conductivity (EC: dS m ⁻¹)	0.25–4.59	1.77	1.31	73.96
3	Sodium adsorption ratio (SAR)	3.18–16.25	7.73	2.46	31.89
4	Residual sodium carbonate (RSC; meq L ⁻¹)	0.65–4.98	2.03	1.08	53.18
5	Chlorine (mg L ⁻¹)	70.90–245.26	143.94	48.54	33.72
6	Boron (mg L ⁻¹)	0.24–3.79	1.74	1.01	58.32

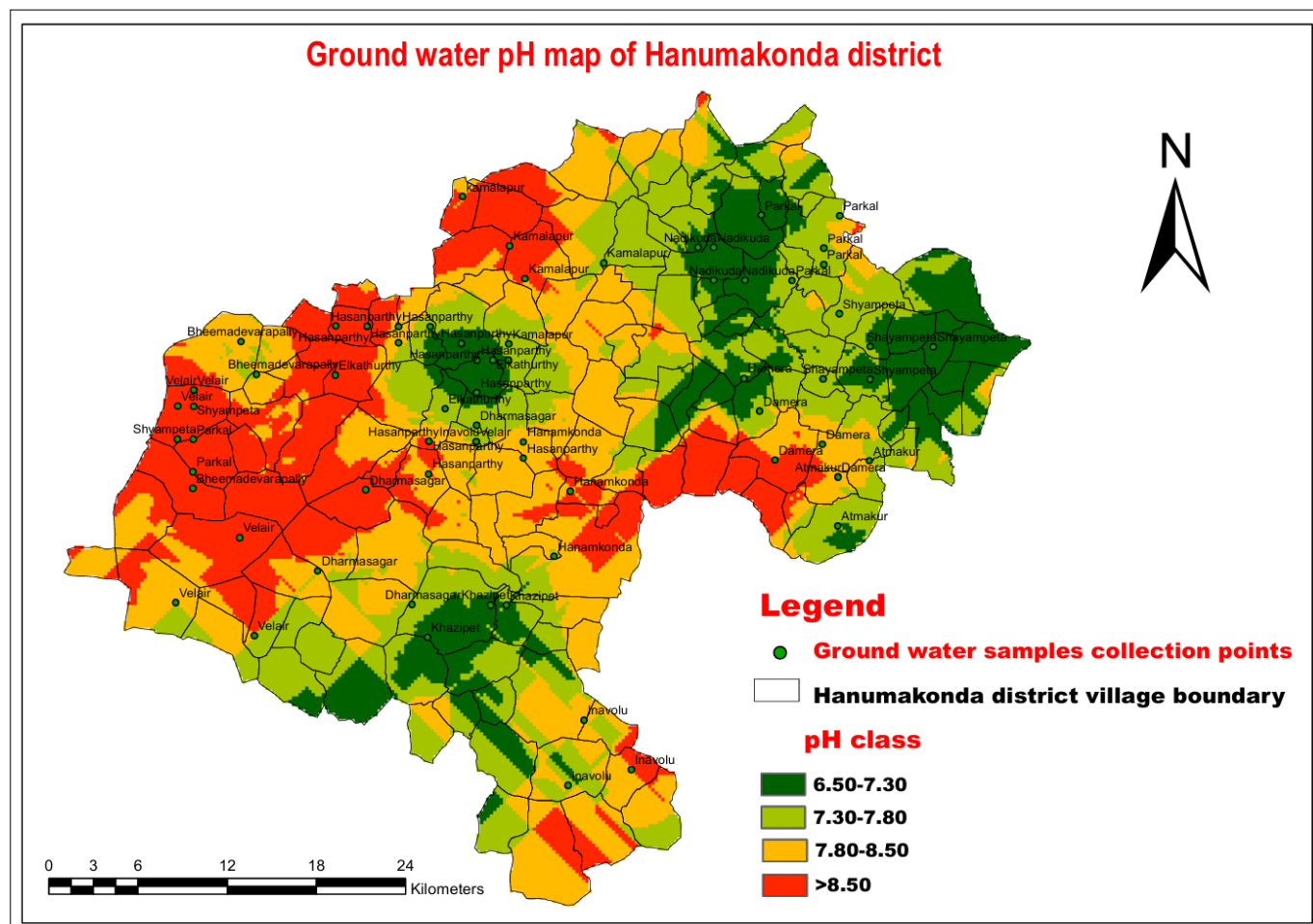


Fig. 3. Spatial distribution of pH in groundwater of Hanumakonda district, Telangana.

Source: ArcGIS software.

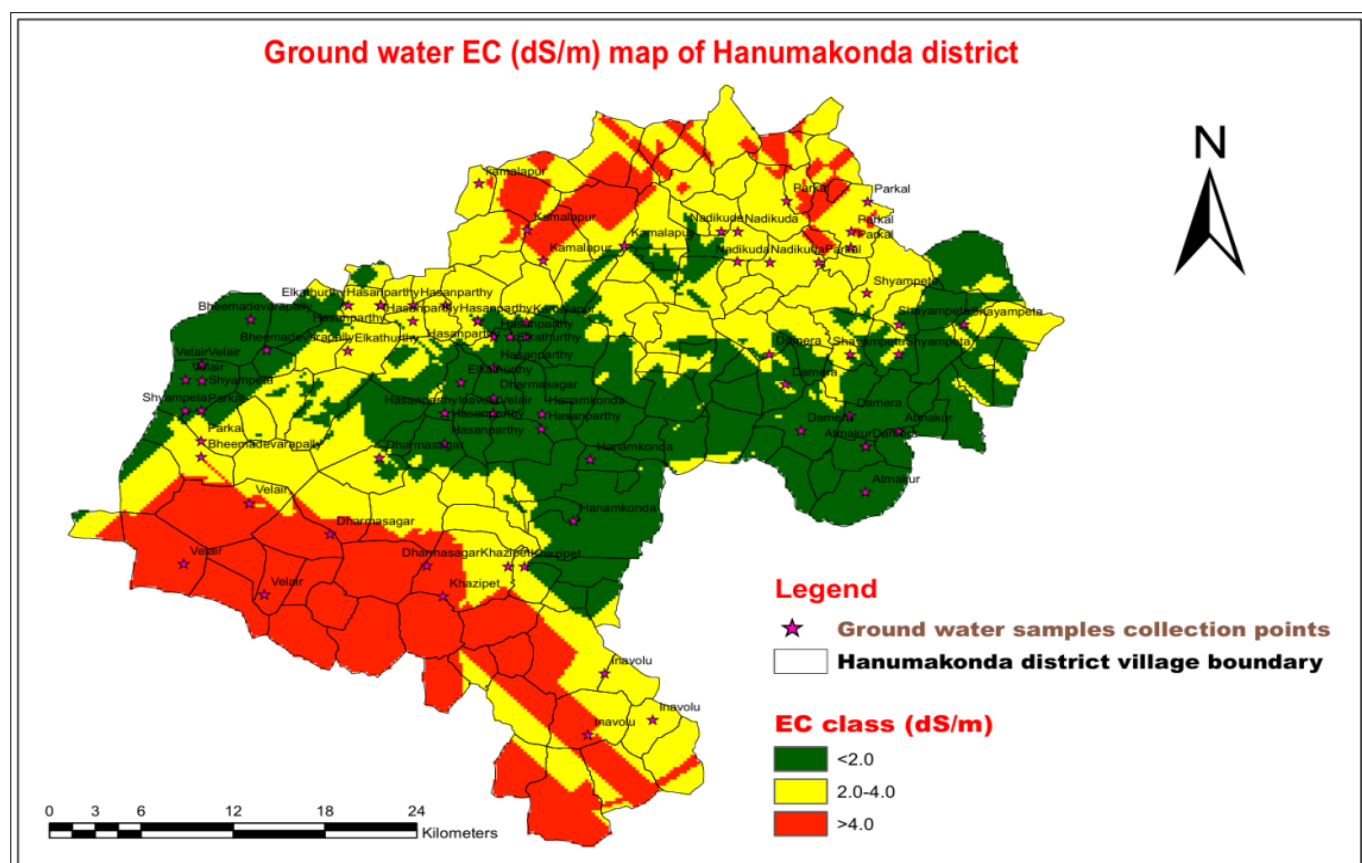


Fig. 4. Spatial distribution of electrical conductivity (dS m^{-1}) class in groundwater of Hanumakonda district, Telangana.

Source: ArcGIS software.

of sodium in groundwater are the weathering of albite (45) and higher levels of sodium are associated with soil sodicity that is harmful to soil health (46, 47). Calcium found in the groundwater is most often from calcium rich minerals in the rocks and soils surrounding the aquifer, such as limestone and dolomite (48). The low level of potassium could be a result of fixation by clay minerals or association with secondary minerals (49–51). The concentrations of major anions, namely carbonate (CO_3^{2-}), bicarbonate (HCO_3^-), chloride (Cl^-) and sulphate (SO_4^{2-}), ranged from 0 to 3.0, 3.0 to 15.6, 0.6 to 66.0 and 0.4 to 15.8 meq L^{-1} , with mean values of 0.2, 8.92, 8.76 and 4.22 meq L^{-1} , respectively. The order of dominance of anions was found to be $\text{HCO}_3^- > \text{Cl}^- > \text{SO}_4^{2-} > \text{CO}_3^{2-}$. Increased bicarbonates may be due to carbonate weathering and the dissolution of minerals like dolomite and shale in aquifers (52, 53). Chloride in groundwater may be derived from natural sources like weathering and dissolution of salt deposits; it may also come from return flows from irrigation (54) and high concentrations of chloride suggest the potential for contamination (55). The sulphates may come from sulphide minerals such as barite and gypsum, from industrially produced or applied sulphates and sulphates in fertilisers (56). Use of soil amendments like gypsum can also be responsible for higher concentrations of sulphate in the groundwater (57).

Table 3. Classification of groundwater samples based on EC (dS m^{-1}) in Hanumakonda district, Telangana, India

EC class (dS m^{-1})	No. of samples	Percentage of samples
0–2	50	64.10
2–4	18	23.08
4–6	10	12.82

Sodium adsorption ratio

The SAR of groundwater in Hanumakonda district of Telangana showed a range from 3.18 to 16.25 with average of 7.73 and standard deviation of 2.46. Table 1 showed that the coefficient of variation was 31.89 %, which suggested that there was high variability. The lowest SAR value (3.18) was recorded in Kamalapur mandal and the highest value (16.25) was recorded in Muppam village of Velair mandal. The spatial distribution revealed that the higher SAR values (> 10) were predominantly concentrated in the parts of Inavolu, Bheemadevarapally, Damara, Hasanparthy, Atmakur and Velair mandals (Fig. 5). The greater SARs in groundwater may be caused by the presence of shale and sodium rich minerals known as feldspar, which liberate more sodium when they are weathered. It may also be affected by the fine montmorillonite clay content of soils, that causes poor drainage and raises sodium concentrations in the groundwater. Higher SAR values in irrigation water can increase the accumulation of exchangeable sodium on the soil exchange complex, resulting in an increase of exchangeable sodium percentage (ESP) and the subsequent development of soil sodicity (58). If the SAR is 0 to 10, generally it is safe and does not pose a sodium hazard and if the SAR is 10 to 18, it is a moderate hazard. From this classification, 94 % of the samples are in the excellent category and 6 % in the good category (Table 4) (59, 60).

Table 4. Classification of groundwater samples based on SAR Hanumakonda district, Telangana

SAR class	No. of samples	Percentage of samples
< 10 (S_1)	73	94
10–18 (S_2)	5	6

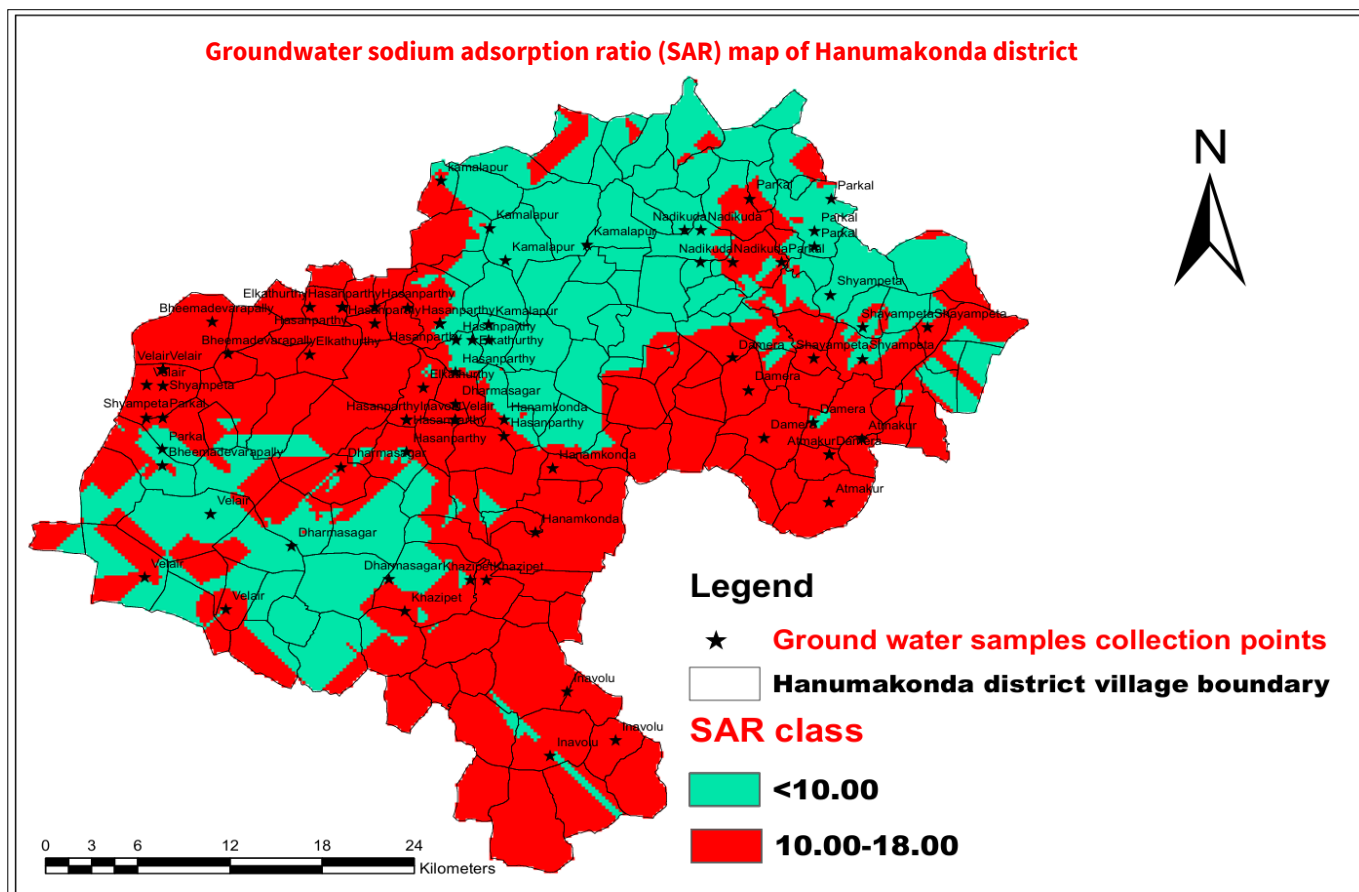


Fig. 5. Spatial distribution of sodium adsorption ratio (SAR) class in groundwater of Hanumakonda district, Telangana.

Source: ArcGIS software.

Residual sodium carbonate (mg L⁻¹)

The RSC is one of the major factors that affect the quality of irrigation water. The range of RSC of groundwater in Hanumakonda district, Telangana was found to be 0.65–4.98 meq L⁻¹ with a mean value of 2.03 and standard deviation of 1.08, coefficient of variance (CV) of 53.18 % which shows high variability (Table 1). Oglapur village in Damera mandal recorded the highest RSC (4.98 meq L⁻¹) which reflects the presence of dominance of sodium ions with carbonate and bicarbonate ions. The lowest RSC value (0.65 meq L⁻¹) was recorded in Singaram village of Inavolu mandal, indicating a low residual carbonate hazard, where carbonate and bicarbonate ions were adequately balanced by calcium and magnesium ions. This suggests a lower risk of sodium accumulation and better suitability of the groundwater for irrigation purposes (61). The spatial distribution of RSC had higher values (> 2.5 meq L⁻¹) in some parts of Hanumakonda, Inavolu and Kamalapur mandals (Fig. 6). This difference could be the result of weathering of shale and other geological formations, resulting in elevated bicarbonate and sodium levels in groundwater. The RSC has a substantial effect on the parameters of irrigation water like pH, EC and SAR (35). The water quality is considered safe (RSC < 1.25 meq L⁻¹), moderately safe (RSC = 1.25–2.50 meq L⁻¹) and unsafe (RSC > 2.50 meq L⁻¹) based on RSC values. The results of the present study indicated that 30.77 % of the samples were safe, 42.31 % moderately suitable and 26.92 % unsuitable (Table 5) (62).

Table 5. Classification of groundwater samples based on RSC (meq L⁻¹) in Hanumakonda district, Telangana

RSC class	Value	No. of samples	Percentage of samples
Safe	< 1.25	24	30.77
Moderately unsafe	1.25–2.50	33	42.31
Unsafe	> 2.50	21	26.92

Chloride content (mg L⁻¹)

The chloride content of the groundwater samples varied from 70.90 mg L⁻¹ to 245.26 mg L⁻¹ with a mean value of 143.94 mg L⁻¹, a standard deviation of 48.54 mg L⁻¹ and a coefficient of variation (CV) of 33.72 %, which is considered having moderate variability (Table 1). The maximum chloride level (245.26 mg L⁻¹) was found in Kammaripet village, Velair mandal and the minimum level (70.90 mg L⁻¹) was recorded in Choutparthy village, Nadikuda mandal.

Groundwater contamination with chloride is caused by saline intrusion, discharge of saline waste into groundwater, discharge of waste from oil wells, discharge of sewage, return flows from irrigation and leaching from waste materials. It can also be a natural phenomenon like the weathering and dissolution of salt deposits (36). High chloride ion levels are usually related to groundwater pollution. Spatial distribution of chloride has revealed

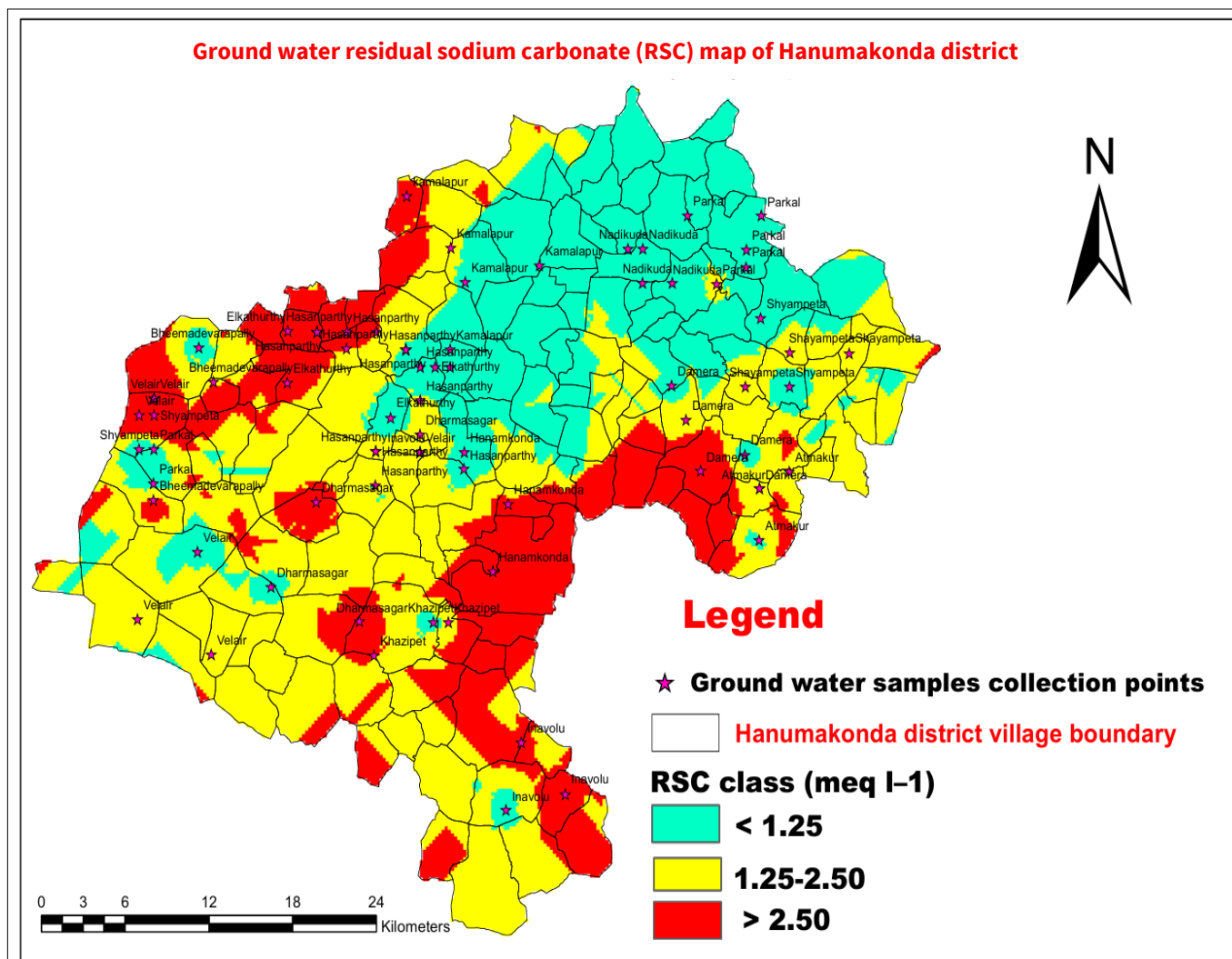


Fig. 6. Spatial distribution of residual sodium carbonate class in groundwater of Hanumakonda district, Telangana.

Source: ArcGIS software.

high concentration (more than 140 mg L^{-1}) in some parts of Inavolu, Kazipet, Dharmasagar, Hasanparthy, Kamalapur and Parkal mandals (Fig. 7). The lower chloride concentration (less than 140 mg L^{-1}) is generally acceptable for the crops and soil while higher chloride concentration may be harmful and can be diluted with good quality water (63). Irrigation water can be classified as safe, moderately safe or unsafe, depending on the chloride concentration in the water $< 140 \text{ mg L}^{-1}$, $140\text{--}350 \text{ mg L}^{-1}$ and $> 350 \text{ mg L}^{-1}$ respectively (34). According to the results of the present study, 46.15 % of the samples were safe and 53.85 % were moderately safe (Table 6).

Table 6. Classification of groundwater samples based on chloride content (mg L^{-1}) in Hanumakonda district, Telangana

Cl class (mg L^{-1})	Value	No. of samples	Percentage of samples
Safe	< 140	36	46.15
Moderately safe	$140\text{--}350$	42	53.85

Boron content (mg L^{-1})

Table 1 shows that the groundwater of Hanumakonda district in Telangana has a higher CV of 58.32 % and a high standard deviation of 1.01, reflecting the high variability of the boron content. The maximum boron content (3.79 mg L^{-1}) was found in Palivelpula village of Hanumakonda mandal and the minimum content (0.24 mg L^{-1}) was found in Seetharampur village of Nadikuda mandal. The spatial distribution of boron showed that the unsafe concentrations ($> 3.0 \text{ mg L}^{-1}$) occurred in certain areas of the mandals viz., Dharmasagar, Kazipet, Hanumakonda and Kamalapur (Fig. 8). The elevated concentration of boron in groundwater could be due to weathering of boron containing minerals and geogenic processes (64). According to the concentration of boron, irrigation water can be classified as safe, moderately safe, moderately unsafe and unsafe (64, 65). In the current study, 60 % of the samples were classified as safe, 11 % moderately safe, 9 % moderately unsafe and 11 % unsafe (Table 7).

Table 7. Classification of groundwater samples based on boron content (mg L^{-1}) in Hanumakonda district, Telangana

Boron class (mg L^{-1})	Value	No. of samples	Percentage of samples
Safe	< 2.0	47	60.26
Moderately safe	$2.0\text{--}2.5$	11	14.10
Moderately unsafe	$2.5\text{--}3.0$	9	11.54
Unsafe	> 3.0	11	14.10

Table 8. Classification of groundwater quality and recommended management practices

Rating	Class	EC (dS m^{-1})	SAR	RSC (meq L^{-1})	No. of samples	Percentage of samples
(I) Good	A	< 2	< 10	< 2.5	38	48.00
(II) Saline						
(i) Marginally saline	B ₁	$2\text{--}4$	< 10	< 2.5	9	12.00
(ii) Saline	B ₂	> 4	< 10	< 2.5	8	10.26
(iii) High SAR saline	B ₃	> 4	> 10	< 2.5	2	2.56
(III) Alkaline water						
(i) Marginally alkaline	C ₁	< 4	< 10	$2.5\text{--}4.0$	13	17.00
(ii) Alkaline	C ₂	< 4	< 10	> 4.0	5	6.41
(iii) Highly alkaline	C ₃	Variable	> 10	> 4.0	3	3.85
Total					78	100

EC: electrical conductivity; SAR: sodium adsorption ratio; RSC: residual sodium carbonate.

Classification of irrigation water

The suitability of groundwater for irrigation was categorised (Table 8) for the groundwater in Hanumakonda district, Telangana. Of the samples tested, approximately 48 % were of good quality, 12 % were marginally saline, 10.26 % saline and 2.56 % high SAR saline. Moreover, a small percentage of the samples were slightly alkaline (17 %), alkaline (6.41 %) and highly alkaline (3.85 %) (Fig. 9). Spatial variations in the groundwater quality indicated that the highly alkaline water mainly occurs in Bheemadevarapally and Elkathurthy mandals (34, 60, 63).

Pearson's correlation analysis

The correlation analysis of irrigation water quality parameters, leaf ionic composition, SPAD values and paddy grain yield showed a few significant relationships, which signifies the influence of water quality on the performance of the crop (Table 9 and Fig. 10). The EC showed a strong negative correlation with paddy grain yield ($r = -0.94^{**}$) and the SPAD value ($r = -0.90^{**}$) and high positive correlation with sodium content in plant leaves ($r = 0.93^{**}$) which indicates that the increased salinity level in the irrigation water adversely affected the yield and chlorophyll content of paddy (66–68), primarily due to increased sodium accumulation in the plant (Table 10). The SAR showed a significant negative correlation with grain yield ($r = -0.35^{**}$) and SPAD value ($r = -0.46^{**}$), while it was highly significantly positive with sodium content in plant leaves ($r = 0.43^{**}$) (Table 10). This indicated sodicity stress also caused a negative impact on crop growth due to increased sodium toxicity and decreased crop physiology efficiency. The RSC had a positive and significant correlation with pH ($r = 0.49^{**}$) and SAR ($r = 0.59^{**}$) and thus it was observed that the water with high bicarbonate/carbonate hazard generally has high pH and the water is sodic in nature. However, RSC did not show a significant direct relationship with grain yield, suggesting that its influence on crop productivity may be indirect through its long-term effects on soil properties and soil sodicity. The grain yield of paddy showed a significant positive correlation with SPAD value ($r = 0.95^{**}$), substantiating the effect of good chlorophyll status on higher productivity. Excessive accumulation of chloride ions in the irrigation water is causing its adverse effect on the grain yield of paddy and this is supported by the significant negative correlation between the two ($r = -0.27^{*}$). Leaf sodium content - Yield also had a highly significant negative correlation ($r = -0.97^{**}$). Leaf chloride content showed a significant negative correlation with yield ($r = -0.27^{*}$). This highlights the high importance of ion toxicity due to accumulation of ions of sodium and chloride which affected paddy yield under poor quality of irrigation water (68–70). Boron had no significant correlation with

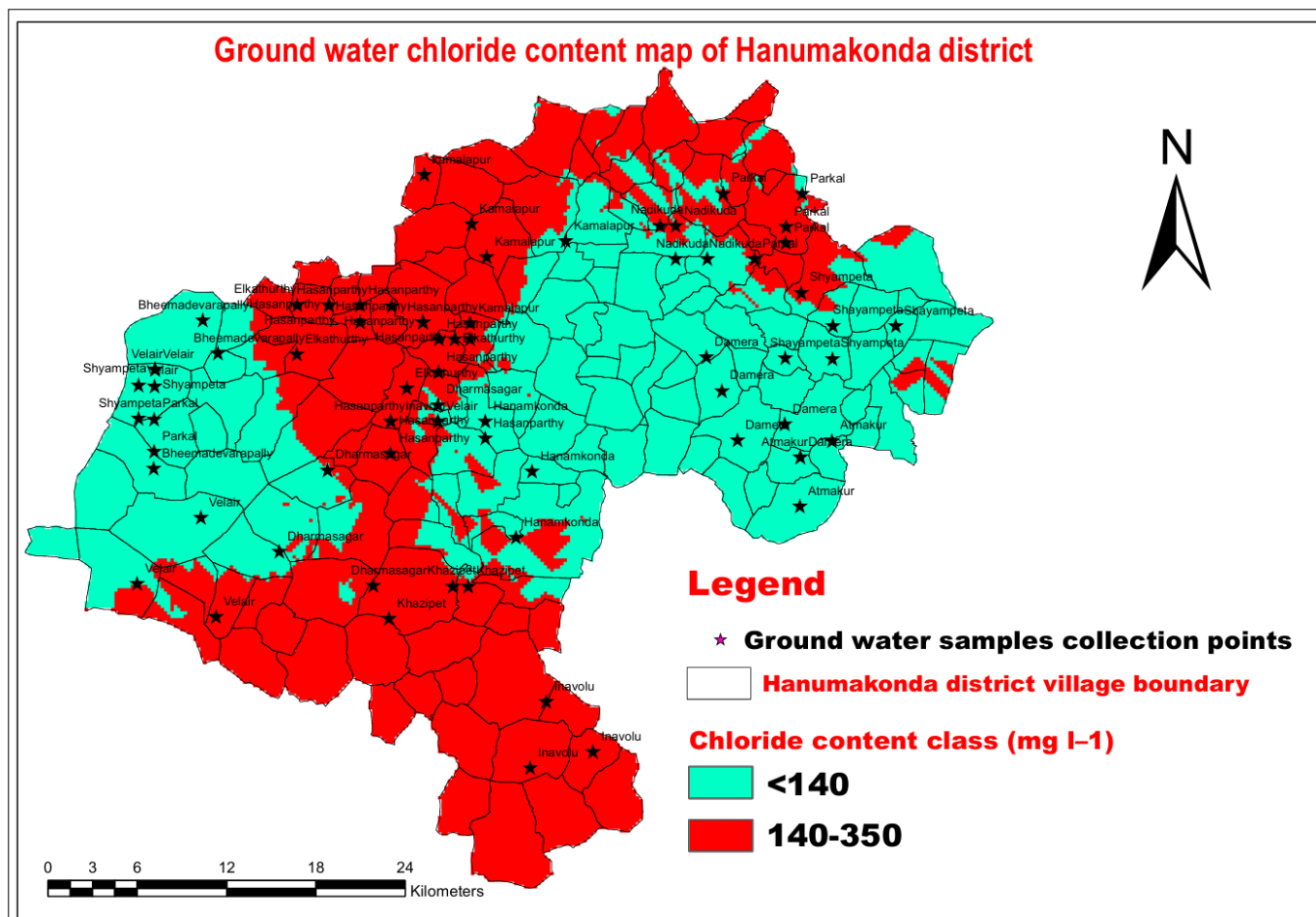


Fig. 7. Spatial distribution of chloride content class in groundwater of Hanumakonda district, Telangana.

Source: ArcGIS software.

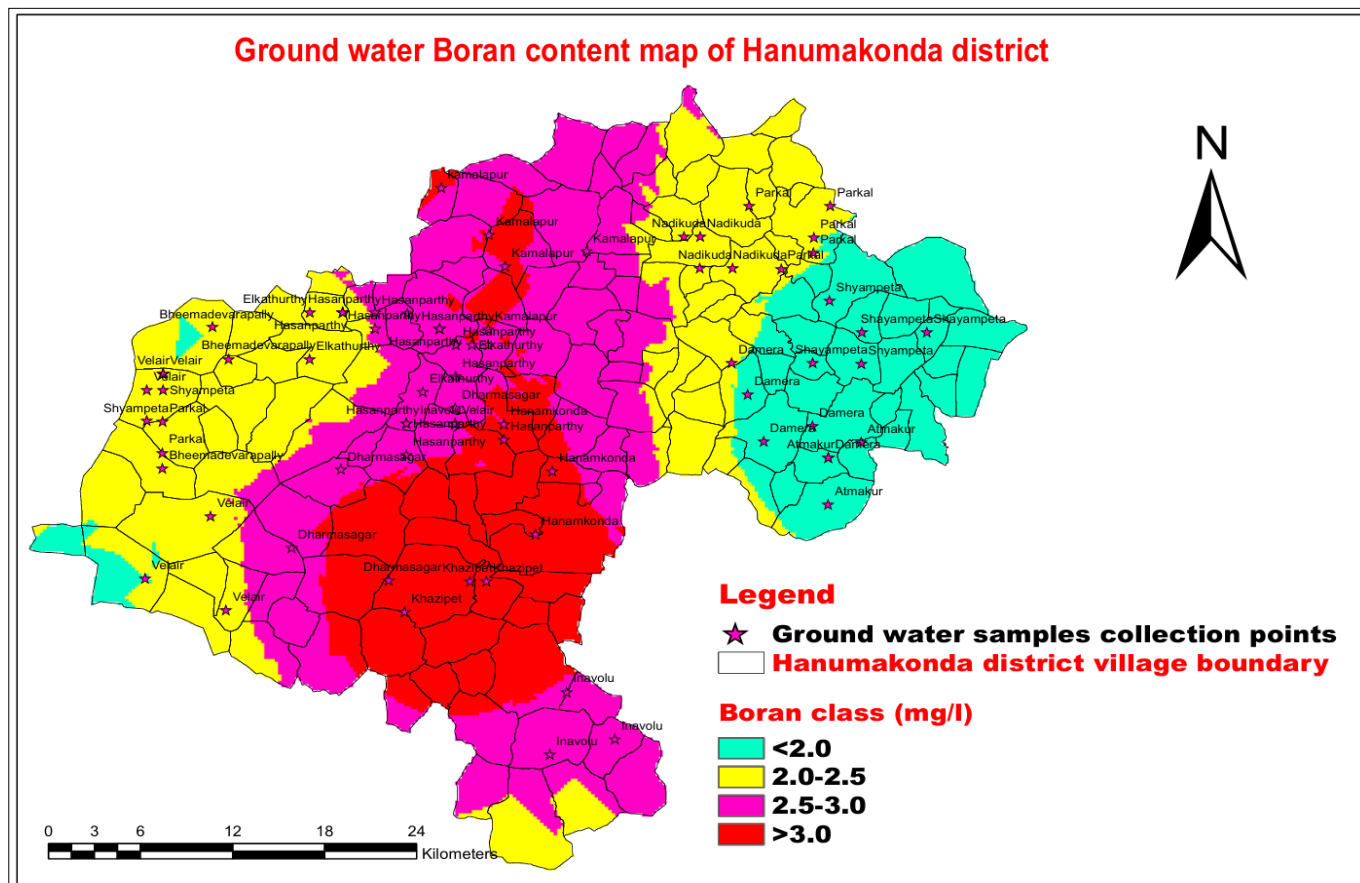
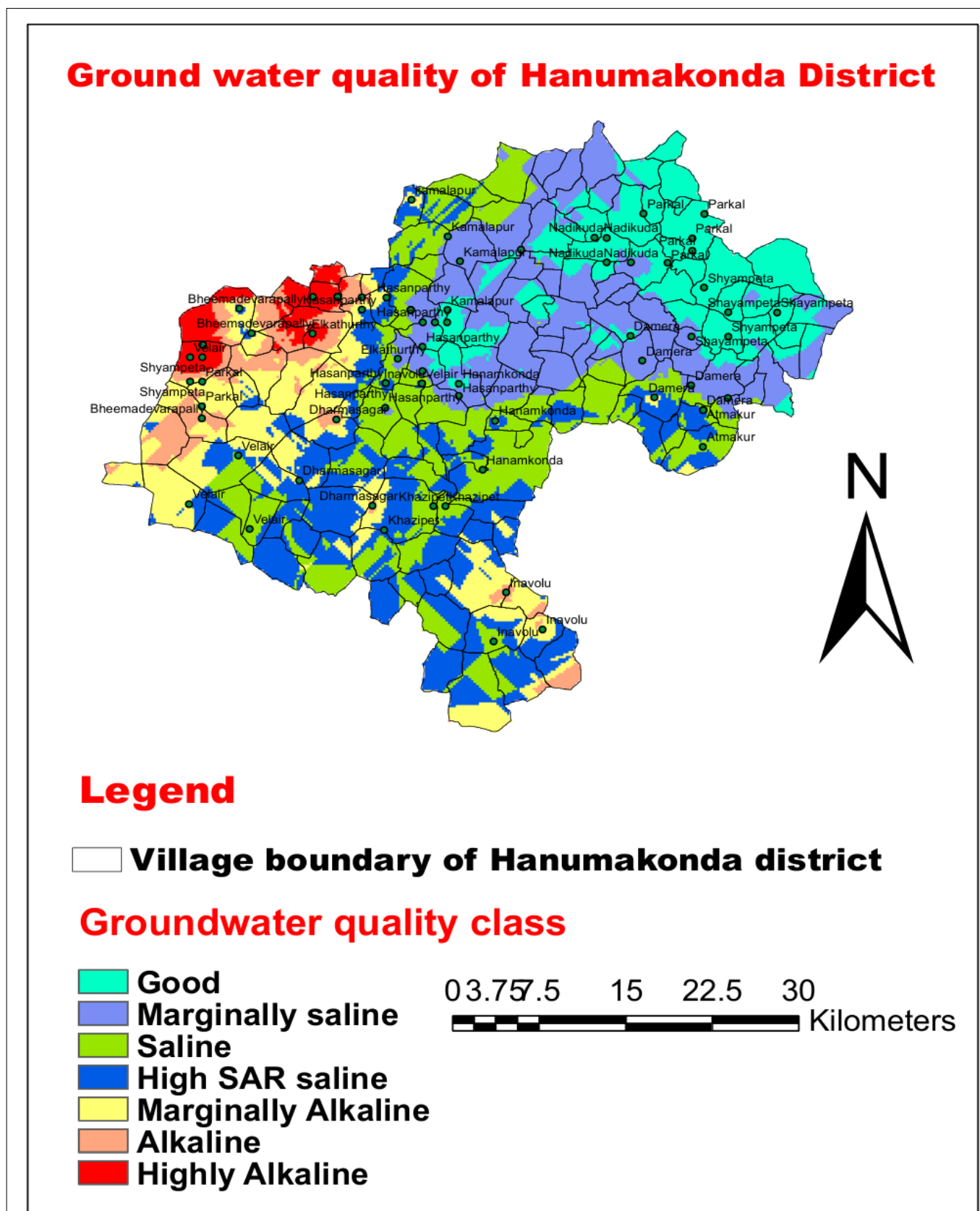


Fig. 8. Spatial distribution of boron content class in groundwater of Hanumakonda district, Telangana.

Source: ArcGIS software.

Table 9. Summary statistics of crop yield and physiological parameters in the study area

Sl. No	Plant parameters	Range	Mean	Standard deviation	Coefficient of variation (CV %)
1	Paddy grain yield (t ha^{-1})	2.66–6.90	5.15	1.10	21.31
2	SPAD Value	22.00–41.92	33.40	5.05	15.12
3	Na content in leaf (%)	0.64–2.50	1.48	0.50	33.53
4	Cl content in leaf (%)	0.87–2.59	1.60	0.44	27.48

**Fig. 9.** Spatial distribution of groundwater quality class of Hanumakonda District, Telangana.

Source: ArcGIS software.

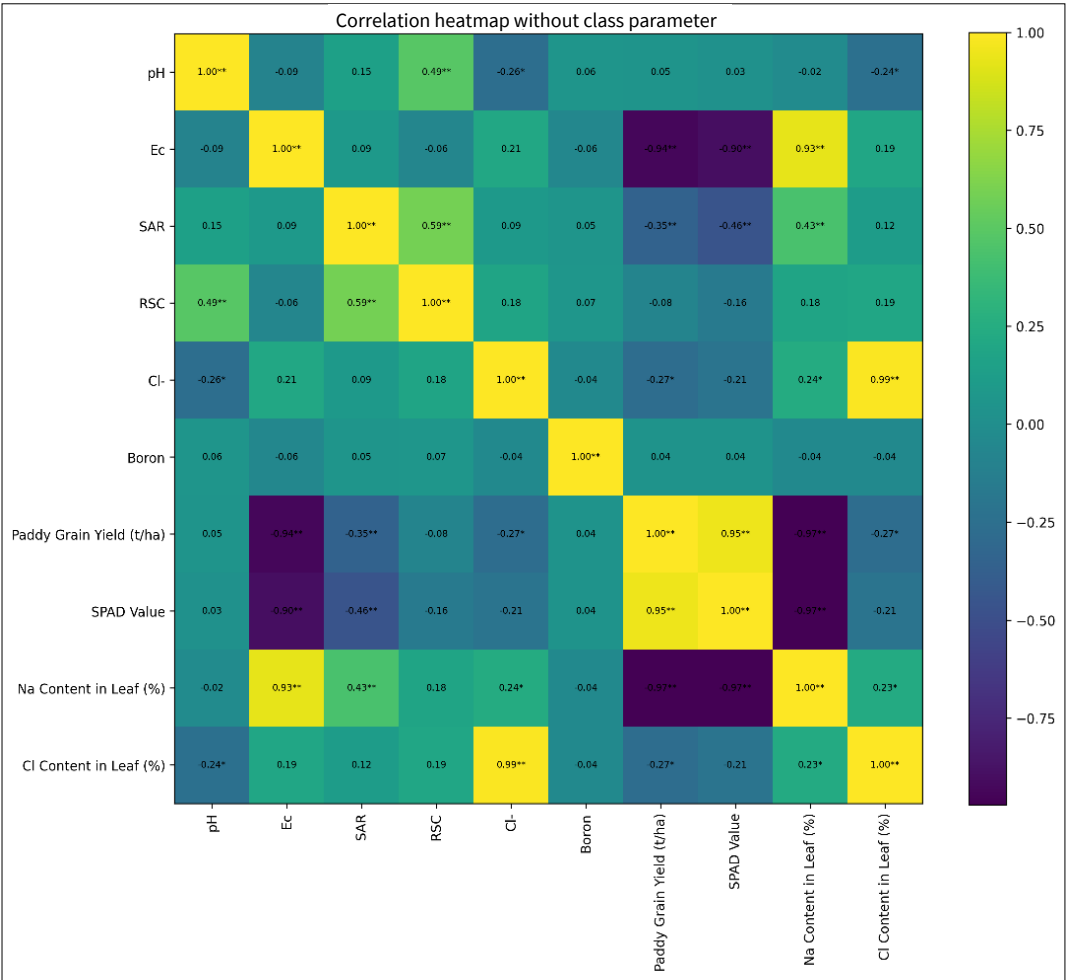


Fig. 10. Correlation matrix between groundwater quality parameters and plant parameters.

Table 10. Correlation matrix between groundwater quality parameters and plant parameters

Class	pH	Ec	SAR	RSC	Cl ⁻	Boron	Paddy grain yield (t/ha)	SPAD value	Na content in leaf (%)	Cl content in leaf (%)
pH	1.00**	-0.09	0.15	0.49**	-0.26*	0.06	0.05	0.03	-0.02	-0.24*
Ec	-0.09	1.00**	0.09	-0.06	0.21	-0.06	-0.94**	-0.90**	0.93**	0.19
SAR	0.15	0.09	1.00**	0.59**	0.09	0.05	-0.35**	-0.46**	0.43**	0.12
RSC	0.49**	-0.06	0.59**	1.00**	0.18	0.07	-0.08	-0.16	0.18	0.19
Cl ⁻	-0.26*	0.21	0.09	0.18	1.00**	-0.04	-0.27*	-0.21	0.24*	0.99**
Boron	0.06	-0.06	0.05	0.07	-0.04	1.00**	0.04	0.04	-0.04	-0.04
Paddy grain yield (t/ha)	0.05	-0.94**	-0.35**	-0.08	-0.27*	0.04	1.00**	0.95**	-0.97**	-0.27*
SPAD value	0.03	-0.90**	-0.46**	-0.16	-0.21	0.04	0.95**	1.00**	-0.97**	-0.21
Na content in leaf (%)	-0.02	0.93**	0.43**	0.18	0.24*	-0.04	-0.97**	-0.97**	1.00**	0.23*
Cl content in leaf (%)	-0.24*	0.19	0.12	0.19	0.99**	-0.04	-0.27*	-0.21	0.23*	1.00**

pH: hydrogen ion concentration; EC: electrical conductivity (dS m⁻¹); SAR: sodium adsorption ratio; RSC: residual sodium carbonate (meq L⁻¹); Cl⁻: chloride concentration (meq L⁻¹); SPAD: Soil plant analysis development chlorophyll meter reading.

yield or with most of the other parameters suggesting that the level of boron in the samples studied was not in a toxicity stress range. Overall, salinity (EC), sodicity (SAR) and chloride hazards in irrigation water had significant impacts on reducing paddy yield through reducing chlorophyll content and increasing the accumulation of harmful ions in the leaves. Hence proper monitoring of water quality in irrigation and using appropriate reclaimed or management practices are necessary for maintaining the productivity of rice.

Conclusion

The study shows that groundwater quality in Hanumakonda district is spatially variable and hydrochemically heterogeneous, being influenced by several hydrogeochemical reactions such as weathering of minerals, ion exchange and evaporation. While 48 %

of the samples were suitable for irrigation, a substantial number of the samples showed salinity and alkalinity hazards which may pose long-term implications for soil health and crop productivity in groundwater-dependent agro-ecosystems. Electrical conductivity (EC), sodium adsorption ratio (SAR) and chloride were found to be the major factors affecting the irrigation suitability among the evaluated parameters. The high negative correlation of EC to grain yield and the SPAD values indicate that salinity causes osmotic stress that restricts plant growth and the high concentrations of sodium and chloride in the leaf tissues indicate that yield losses are due to the toxicity of ions. This is an approach that is different from traditional studies, which are mainly descriptive and connects directly the quality of the groundwater with a physiological change of the crop in field conditions. The combination of hydrochemical assessment with GIS based spatial mapping and crop performance

indicators is a novel and effective approach to irrigation water assessment. On a global scale, the results have important implications for the sustainability of semi-arid regions that are becoming more dependent on groundwater in the face of climate variability. Adopting site specific management practices, such as conjunctive water use, gypsum applications and better drainage are critical for reducing salinity and sodicity threats. The results of this study provide a useful framework for sustainable groundwater management and support the development of climate-smart agriculture. The spatial groundwater quality maps generated in this study can assist farmers in identifying areas with salinity and sodicity risks and adopting appropriate management practices. Farmers using groundwater with elevated EC, SAR, RSC and chloride levels are advised to implement site-specific nutrient management, apply suitable soil amendments such as gypsum where necessary, improve drainage conditions, incorporate organic manures and select salt-tolerant crop varieties to minimise adverse effects on crop productivity. Periodic monitoring of groundwater quality and soil health is also recommended to prevent the long-term buildup of salts and maintain agricultural sustainability. Furthermore, the findings can support extension agencies and policymakers in developing location-specific irrigation water management strategies and climate-resilient agricultural interventions for sustainable crop production. Future research should focus on long-term monitoring of groundwater quality and soil properties to better understand the cumulative impacts of saline irrigation on soil degradation and crop performance. Further studies should investigate varietal differences in salt tolerance among rice cultivars, evaluate the effectiveness of different soil and water management practices under field conditions and integrate climate change projections with groundwater quality assessments to develop resilient and sustainable irrigation strategies for semi-arid agricultural regions.

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Authors' contributions

CHR conceived and designed the study, supervised the research work, carried out groundwater sample collection and laboratory analysis, interpreted the results and prepared the manuscript draft. JK contributed to data interpretation, statistical analysis and manuscript revision. RUR assisted in groundwater sample collection, laboratory analysis and compilation of field data. VBP contributed to GIS mapping, spatial analysis, data visualisation and manuscript editing. SD assisted in crop data collection, plant analysis and literature review. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT to check grammar. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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