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Assessment of spatial and temporal variability of salinity in coastal water bodies of Udupi District

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Abstract

An investigation was conducted to assess the spatial and temporal variations in water quality during the pre- and post-monsoon seasons in the coastal aquifers of the study area. A total of 51 representative water samples were randomly collected from different geographical locations during both seasons from seawater, bore wells, lakes, open wells, rivers, and streams, with geographical coordinates recorded for each sampling site. The results showed that the pH of the water samples during the pre- and post-monsoon seasons ranged from 5.60 to 7.97 and 5.75 to 8.44, with mean values of 6.93 and 7.29, respectively, indicating conditions ranging from moderately acidic to moderately alkaline. The electrical conductivity (EC) ranged from 0.13 to 58.90 dS m⁻¹ during the pre-monsoon season and from 0.11 to 32.90 dS m⁻¹ during the post-monsoon season, with mean values of 8.80 and 5.26 dS m⁻¹, respectively. Among the major cations and anions, Na⁺ and Cl⁻ were predominant in groundwater, followed by Mg²⁺, Ca²⁺, K⁺, SO₄²⁻, HCO₃⁻, and CO₃²⁻ during both seasons. The mean boron concentration was 18.18 and 15.40 meq L⁻¹ during the pre- and post-monsoon seasons, respectively. The sodium adsorption ratio (SAR) ranged from 0.07 to 18.93 and from 0.06 to 25.22, while the residual sodium carbonate (RSC) ranged from -96.80 to -0.70 meq L⁻¹ and -85.60 to -0.40 meq L⁻¹ during the pre- and post-monsoon seasons, respectively. The mean SAR and RSC values were 3.54 and -16.82 meq L⁻¹ in the pre-monsoon season and 3.36 and -13.80 meq L⁻¹ in the post-monsoon season, respectively. Based on EC, 7.84% and 11.76% of the samples had EC < 0.25 dS m⁻¹, whereas 31.38% and 29.42% had EC > 4 dS m⁻¹ during the pre- and post-monsoon seasons, respectively. Regarding SAR, 1.96% of the samples were classified as moderately unsafe in both seasons. According to CSSRI guidelines, 66.67% and 19.61% of the samples were classified as good and higher-SAR saline, respectively, during the pre-monsoon season, compared with 64.71% and 13.73%, respectively, during the post-monsoon season. Overall, the results indicate considerable spatial and seasonal variability in water quality, highlighting the influence of salinity and associated ion concentrations on the suitability of water resources for agricultural use in the coastal aquifers.

Keywords: CSSRI, Electrical conductivity, SAR and Spatial - temporal water quality

Introduction

The coastal zone represents a dynamic interface between terrestrial and marine environments, where both land-based and oceanic processes interact and influence the physical and chemical characteristics of the region ^[1]. India has a coastline of approximately 7,516.6 km, with its peninsular region bounded by the Arabian Sea to the west, the Bay of Bengal to the east, and the Indian Ocean to the south. The coastal area accounts for approximately 15.14% of the country's total geographical area. Karnataka has a coastline of about 320 km, and its coastal region constitutes approximately 6.09% of the state's geographical area ^[2]. Resource evaluation and management in coastal regions are considerably more complex than in inland areas because of the close interaction between freshwater and seawater systems. Therefore, reliable information on the characteristics, potential, and limitations of soil and water resources is essential for the planned and sustainable development of coastal areas.

In coastal regions, groundwater is a major source of freshwater and is extensively exploited to meet increasing domestic, agricultural, and industrial water demands ^[3]. Excessive groundwater withdrawal can disturb the hydrodynamic equilibrium between freshwater and seawater within coastal aquifers, resulting in the inland movement of seawater and deterioration of freshwater resources ^[4-6]. The relationship between freshwater and seawater distribution in coastal aquifers

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is commonly described by the Ghyben-Herzberg relationship [7]. Under simplified hydrostatic conditions, an approximately 1 m increase in freshwater hydraulic head can correspond to an approximately 40 m increase in the freshwater-saturated zone below sea level. Conversely, a decline in groundwater levels below mean sea level can reverse the hydraulic gradient and promote the inland movement of seawater into coastal aquifers [8, 9]. This process, known as seawater intrusion, is a major cause of deterioration of coastal groundwater quality. Seawater intrusion can adversely affect agricultural and industrial activities and may also have implications for the health and living conditions of coastal communities [10].

Understanding hydrological processes, including changes in groundwater levels, groundwater quality, and tidal fluctuations, is essential for effective management of coastal aquifers. Coastal zones support a substantial proportion of the global population, particularly in low-lying and deltaic regions, while coastal aquifers provide important freshwater resources for domestic consumption and irrigation [11, 12]. Groundwater level is an important indicator for assessing spatial and temporal variations in coastal groundwater systems [13]. It is influenced by several interacting factors, including precipitation, evaporation, groundwater abstraction, recharge, tidal fluctuations, and climatic variability. Changes in precipitation and evaporation associated with climate variability and climate change can consequently influence groundwater-level fluctuations and freshwater availability [14].

Irrigation water invariably contains dissolved salts, regardless of its source; however, the total concentration and composition of these salts determine its suitability for irrigation. Among the major ions, sodium is of particular importance because excessive sodium relative to calcium and magnesium can adversely affect soil structure, infiltration, and permeability. Coastal groundwater systems are particularly vulnerable to salinization because of seawater intrusion and other processes associated with intensive groundwater exploitation. Therefore, assessment of salinity and related water-quality parameters is essential for determining the suitability of coastal water resources for agricultural use. In view of these concerns, the present study was undertaken to assess the spatial and temporal variability of salinity and associated water-quality characteristics in the coastal water resources of Udupi District, Karnataka, during the pre- and post-monsoon seasons. The study considers water from different sources, including groundwater and surface-water bodies, to evaluate seasonal variations in major physicochemical parameters and irrigation-water quality and to identify the potential influence of salinity

and seawater intrusion on the suitability of these water resources for agricultural purposes.

Materials and Methods

Study Area

The study area comprises part of the coastal region of Brahmapara Taluk, Udupi District, Karnataka, covering approximately 12,594.79 ha (Fig. 1). The area falls within the coastal agro-climatic zone of Karnataka (Agro-climatic Zone No. 10). Udupi District is located between 74°45' and 74°46' E longitudes and 13°24'45" and 13°25'30" N latitudes. The region receives an average annual rainfall of approximately 4,672 mm, and the study area has a mean elevation of about 27 m above mean sea level.

Water Sampling and Analysis

A total of 51 representative water samples were collected during both the pre- and post-monsoon seasons from different water sources, including the sea, bore wells, lakes, open wells, rivers, and streams, to represent the spatial variability of the study area. The geographical coordinates of each sampling location were recorded using appropriate geographic positioning equipment, and the sampling sites are shown in Fig. 2 and Plate 1.

Water samples were collected during April-May 2022 for the pre-monsoon season and October-November 2022 for the post-monsoon season. Samples were collected in clean, capped, high-density polyethylene (HDPE) bottles. Approximately 1 mL of toluene was added to each sample to minimize biological activity during storage and transportation. The samples were subsequently analyzed for major salinity and sodicity-related water-quality parameters, including pH, electrical conductivity (EC), major cations [Ca^{2+} , Mg^{2+} , Na^+ , and K^+], and major anions [Cl^- , SO_4^{2-} , CO_3^{2-} , and HCO_3^-], following the standard procedures described by Richards [15].

Calcium (Ca^{2+}) and magnesium (Mg^{2+}) concentrations were determined using the Versenate titration method, whereas sodium (Na^+) and potassium (K^+) concentrations were measured using flame photometry. Carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) concentrations were determined by titration with standard acid. Chloride (Cl^-) was estimated by titration with silver nitrate, while sulfate (SO_4^{2-}) was determined by precipitation as barium sulfate. The analytical results were subsequently used to calculate the sodium adsorption ratio (SAR) and residual sodium carbonate (RSC) using the following equations:

$$\text{SAR} = \frac{\text{Na}^+}{\sqrt{\frac{\text{Ca}^{2+} + \text{Mg}^{2+}}{2}}}$$

$$\text{RSC} = (\text{CO}_3^{2-} + \text{HCO}_3^-) - (\text{Ca}^{2+} + \text{Mg}^{2+}); \text{mmol L}^{-1}$$

Considering EC, SAR and RSC, underground water quality for irrigation was categorized based on the criteria as outlined by

Minhas [16] as detailed below (Table 1).

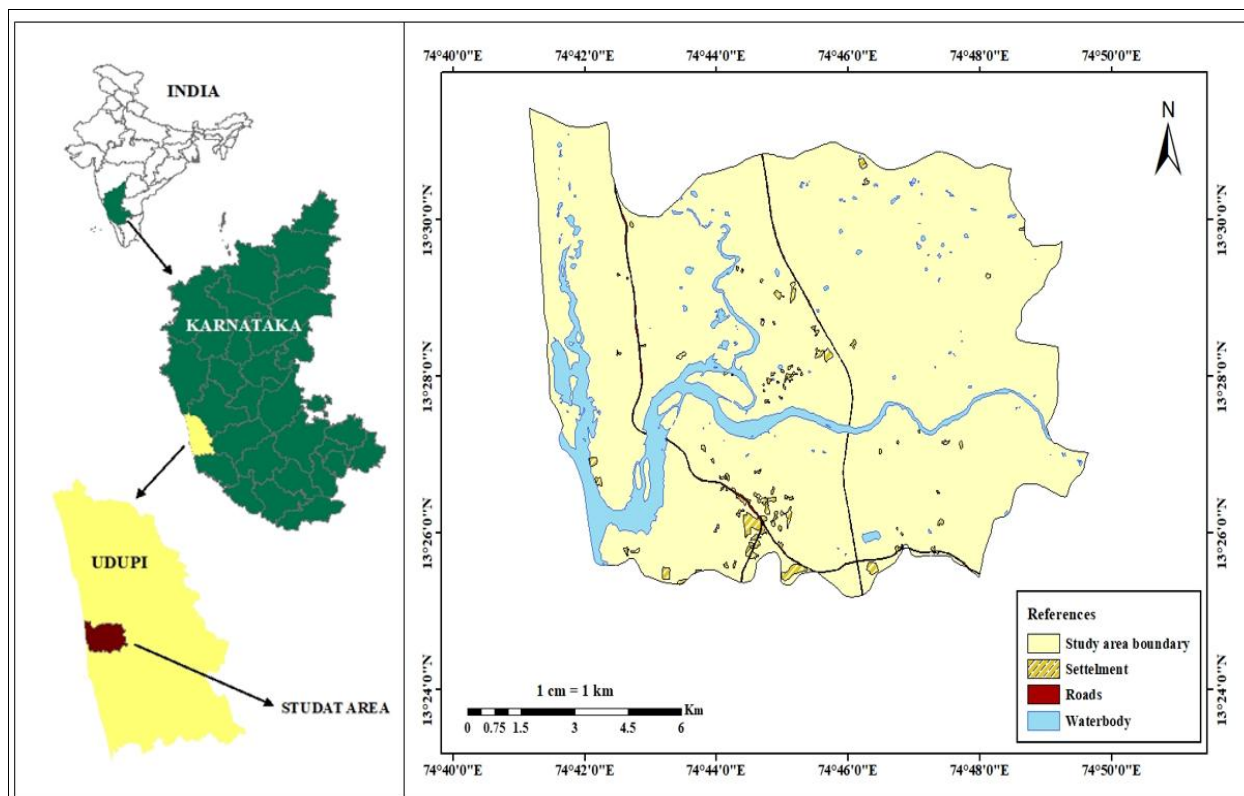


Fig 1: Location map of the study area

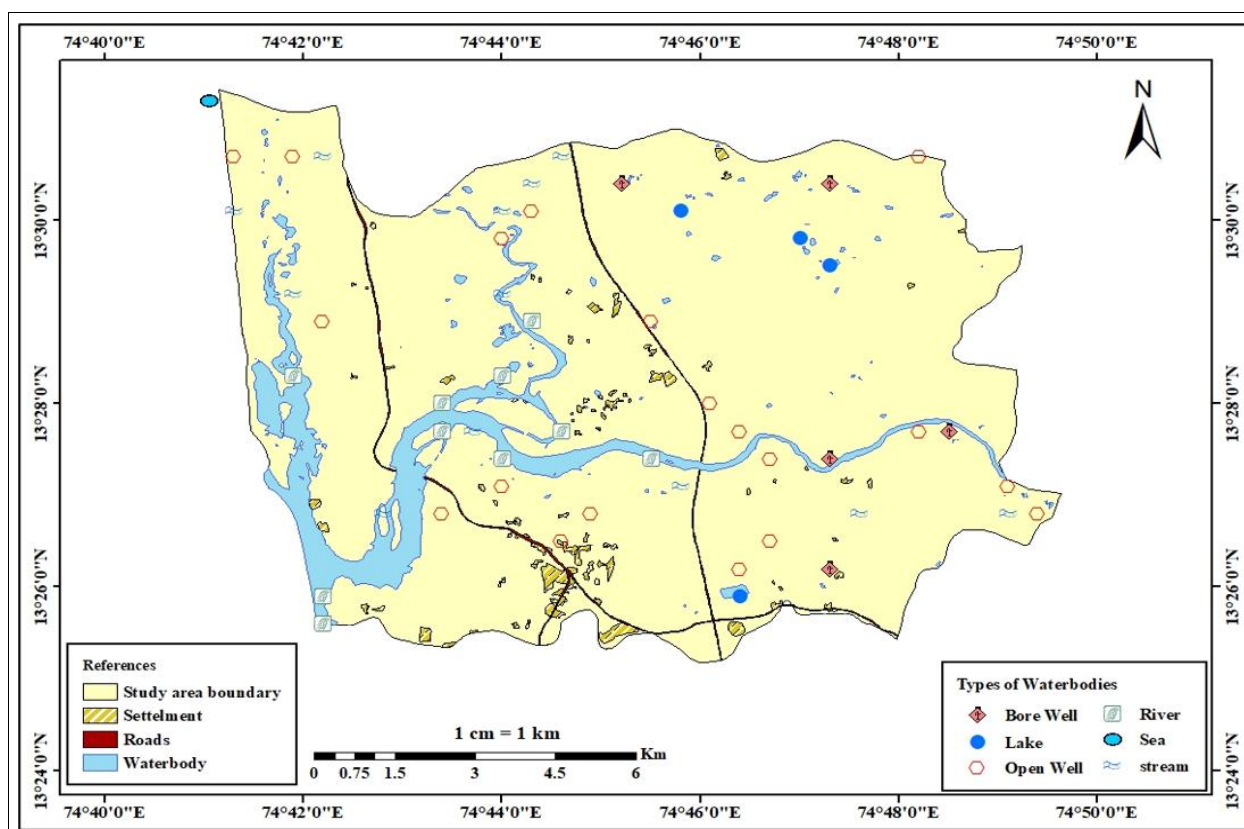


Fig 2: Water sampling points of the study area

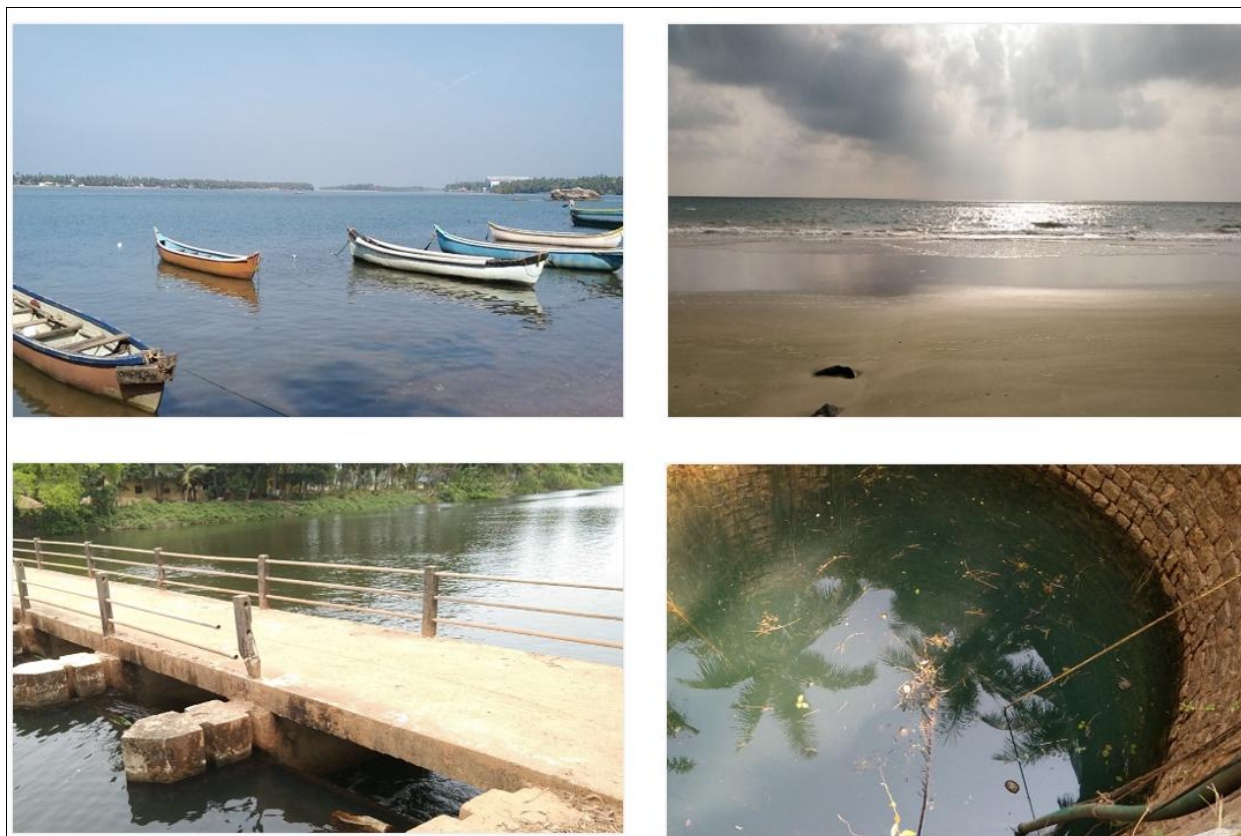


Plate 1: Water sample collection sources in the study area

Table 1: Overall classification of irrigation water given by Central Soil Salinity Research Institute (CSSRI), Karnal

	EC (dS m ⁻¹)	SAR	RSC (mmol L ⁻¹)
I. Good water	<2.0	<10.0	<2.50
II. Saline water			
a. Marginally saline	2- 4	<10.0	<2.50
b. Saline	>4.0	<10.0	<2.50
c. High SAR saline	>4.0	>10.0	<2.50
III Alkali water			
a Marginally alkali	<4.0	<10.0	2.50-4.0
b. Alkali	<4.0	<10.0	>4.0
c. Highly alkali	Variable	>10.0	>4.0

Results and Discussion

Concentration of cations and anions of water samples collected from study area from the pre- and post-monsoon season.

The results on the concentration of different soluble cations and anions viz., calcium, magnesium, sodium, potassium, carbonates, bicarbonates, chlorides, sulphates and boron in water samples collected from study area from pre- and post-monsoon season are presented in Table 2 and 3.

Calcium

The results revealed that the Ca²⁺ concentration in the water samples ranged from 0.70 to 21.90 meq L⁻¹ during the pre-monsoon season, with a mean value of 5.24 meq L⁻¹, and from 0.50 to 18.90 meq L⁻¹ during the post-monsoon season, with a mean value of 3.85 meq L⁻¹, respectively. The corresponding standard deviations were 5.95 and 4.87 meq L⁻¹, while the coefficients of variation were 113.49% and 127.00% during the pre- and post-monsoon seasons, respectively. The high coefficients of variation indicate considerable spatial variability in Ca²⁺ concentrations across the study area.

The relatively higher mean Ca²⁺ concentration observed during the pre-monsoon season may be associated with increased evaporation and concentration of dissolved ions under comparatively dry conditions. In addition, the dissolution of calcium-bearing minerals, particularly calcite and dolomite, may contribute to the Ca²⁺ concentration of groundwater. Reverse cation exchange, in which Na⁺ in the aquifer matrix is exchanged with Ca²⁺ and Mg²⁺ in solution, may also contribute to elevated calcium concentrations at specific locations. The observed seasonal variation is consistent with the findings reported by Sreedevi *et al.* [17] and Singh *et al.* [18].

Magnesium

The data presented in Table 2 showed that the Mg²⁺ concentration in the water samples ranged from 0.60 to 79.80 meq L⁻¹ during the pre-monsoon season and from 0.20 to 72.60 meq L⁻¹ during the post-monsoon season. The mean Mg²⁺ concentration was 12.51 meq L⁻¹ during the pre-monsoon season and 10.43 meq L⁻¹ during the post-monsoon season. The corresponding standard deviations were 17.73 and 16.80 meq L⁻¹, while the coefficients of variation were 141.76% and 161.00%, respectively. The high coefficients of variation

indicate substantial spatial variability in Mg^{2+} concentrations among the sampling locations.

The relatively higher mean Mg^{2+} concentration during the pre-monsoon season may be attributed to increased evaporation and concentration of dissolved ions, together with the weathering and dissolution of dolomite and other magnesium-bearing minerals. In coastal aquifers, Mg^{2+} concentrations may also be influenced by seawater mixing and ion-exchange processes. In particular, reverse cation exchange can occur when Na^+ in solution is exchanged with Ca^{2+} and Mg^{2+} associated with exchange sites in the aquifer material, thereby contributing to increased concentrations of Ca^{2+} and Mg^{2+} in groundwater.

From an irrigation perspective, excessive Mg^{2+} may adversely influence soil structure and hydraulic properties under certain conditions, particularly when accompanied by high concentrations of other salts. However, the majority of the samples were within the acceptable range according to the adopted irrigation-water classification. Therefore, the observed Mg^{2+} concentrations should be interpreted together with EC, Ca^{2+} , Na^+ , and other major ions rather than considered independently. Similar variations in magnesium concentration in groundwater have been reported by Savalia *et al.* [19] and Yadav *et al.* [20].

Sodium

The results presented in Table 2 indicate that the Na^+ concentration in the water samples ranged from 0.13 to 87.56 meq L^{-1} during the pre-monsoon season and from 0.07 to 80.34 meq L^{-1} during the post-monsoon season. The mean Na^+ concentration was 14.85 meq L^{-1} during the pre-monsoon season and 12.44 meq L^{-1} during the post-monsoon season. The corresponding standard deviations were 24.70 and 20.54 meq L^{-1} , while the coefficients of variation were 166.32% and 165.14%, respectively. The high coefficients of variation indicate pronounced spatial variability in sodium concentration across the study area.

The comparatively higher mean Na^+ concentration during the pre-monsoon season may be associated with enhanced evaporation, reduced freshwater recharge, and concentration of dissolved salts. In the coastal region, seawater intrusion or mixing with saline water may also contribute substantially to elevated Na^+ concentrations. In addition, weathering of sodium-bearing minerals, including feldspars, can contribute Na^+ to groundwater.

From an irrigation perspective, high Na^+ concentrations are of particular concern because sodium can become adsorbed onto soil cation-exchange sites, displacing Ca^{2+} and Mg^{2+} . Prolonged application of high-sodium irrigation water may consequently promote soil aggregate dispersion, reduced infiltration and hydraulic conductivity, surface crusting, and deterioration of soil physical conditions, thereby adversely affecting seedling emergence and crop growth [21, 22]. The predominance of Na^+ in the water samples may therefore be an important indicator of salinity and sodicity hazards in the coastal aquifers of the study area.

The observed sodium concentrations are consistent with the findings reported by Verma *et al.* [23]. High-sodium irrigation water can adversely affect soil fertility and crop productivity when applied continuously without appropriate soil and water management practices [24, 25]. Therefore, Na^+ concentration should be evaluated in conjunction with EC and SAR to provide a more reliable assessment of the suitability of the water for irrigation.

Potassium

The data presented in Table 2 showed that the soluble K^+ concentration in the water samples ranged from 0.01 to 16.55 meq L^{-1} , with a mean value of 2.75 meq L^{-1} during the pre-monsoon season. During the post-monsoon season, K^+ concentration ranged from 0.01 to 12.63 meq L^{-1} , with a mean value of 2.05 meq L^{-1} . The standard deviations were 4.62 and 3.67 meq L^{-1} , while the coefficients of variation were 168.17% and 179.10% during the pre- and post-monsoon seasons, respectively. The high coefficients of variation indicate substantial spatial variability in soluble K^+ concentration among the sampling locations.

The relatively higher K^+ concentration observed during the pre-monsoon season may be associated with rock-water interactions, longer groundwater residence time, and reduced dilution under lower recharge conditions. Potassium is released into groundwater primarily through the weathering of K-bearing minerals, particularly feldspars and micas. However, compared with Na^+ and Ca^{2+} , K^+ generally exhibits greater retention in soils and aquifer materials because of fixation and adsorption onto clay minerals. Consequently, its concentration in groundwater is influenced by mineral weathering, cation exchange, clay-mineral interactions, and anthropogenic inputs.

Elevated K^+ concentrations in groundwater may also occur locally due to agricultural inputs, particularly the application of potassium-containing fertilizers and organic manures, especially where wells are located close to intensively cultivated areas [26, 27]. The lower K^+ concentrations observed during the post-monsoon season may be related to dilution resulting from monsoonal recharge and increased groundwater replenishment. Similar variations in potassium concentration have been reported by Mahmud *et al.* [28] and Mustapha *et al.* [29].

Among the major cations, Na^+ was the dominant ion, followed by Ca^{2+} , Mg^{2+} , and K^+ in several samples. The relative abundance of cations in the irrigation water generally followed the order $Na^+ > Ca^{2+} > Mg^{2+} > K^+$, consistent with the observations of Rajput and Polara [30]. The predominance of Na^+ may be associated with seawater mixing/intrusion, mineral weathering, ion-exchange processes, and concentration of dissolved salts in the coastal aquifer.

The major cationic composition of the water samples was also characterized by the order $Na^+ > Mg^{2+} > Ca^{2+} > K^+$, indicating that Mg^{2+} concentrations exceeded Ca^{2+} concentrations in the study area (Table 2). The mean Mg^{2+} concentrations of 12.51 and 10.43 meq L^{-1} during the pre- and post-monsoon seasons, respectively, were considerably higher than the corresponding Ca^{2+} concentrations of 5.24 and 3.85 meq L^{-1} . Water samples having a Mg^{2+}/Ca^{2+} ratio >1.5 warrant attention because excessive Mg^{2+} relative to Ca^{2+} may adversely affect soil physical properties and infiltration under prolonged irrigation.

The occurrence of elevated Mg^{2+}/Ca^{2+} ratios, particularly in samples with medium salinity (2-4 dS m^{-1}), indicates that salinity hazard may coexist with a potential magnesium-related soil hazard. The apparent Mg hazard increased with increasing salinity, suggesting that both total salinity and the relative proportions of divalent cations should be considered when evaluating irrigation-water quality. The relatively high Mg^{2+} concentration may reflect seawater influence, dissolution of Mg-bearing minerals, and ion-exchange processes within the coastal aquifer. These findings emphasize the importance of evaluating Mg^{2+} together with EC, SAR, and the Ca^{2+}/Mg^{2+} balance when assessing the long-term suitability of coastal groundwater for irrigation.

Carbonates

The CO_3^{2-} concentration in the water samples ranged from 0.10 to 0.70 meq L^{-1} , with a mean value of 0.32 meq L^{-1} , during the pre-monsoon season and from 0.10 to 0.50 meq L^{-1} , with a mean value of 0.23 meq L^{-1} , during the post-monsoon season. The corresponding standard deviations were 0.41 and 0.10 meq L^{-1} , while the coefficients of variation were 44.26% and 42.24%, respectively (Table 3). The relatively moderate coefficients of variation indicate appreciable spatial variability in carbonate concentration across the sampling locations.

The presence of CO_3^{2-} in groundwater is primarily controlled by carbonate equilibria, mineral weathering, and the dissolution of carbonate minerals. Carbon dioxide dissolved in water forms carbonic acid, which participates in mineral-weathering reactions and contributes to the bicarbonate-carbonate system. The relative proportions of CO_3^{2-} and HCO_3^- are strongly influenced by pH, with carbonate becoming increasingly dominant as pH increases. In coastal aquifers, these equilibria may additionally be influenced by seawater mixing, groundwater residence time, and interactions between groundwater and carbonate-bearing sediments or minerals.

The slightly higher mean CO_3^{2-} concentration during the pre-monsoon season may be associated with greater evaporation and reduced dilution, whereas monsoonal recharge during the post-monsoon period may have contributed to lower concentrations. The observed results are in agreement with the findings of Sadashivaiah *et al.* [31], Emamgholizadeh [32], and Ramkumar *et al.* [33].

Because carbonate and bicarbonate contribute to residual sodium carbonate (RSC), their concentrations are particularly important when evaluating the suitability of water for irrigation. Therefore, the carbonate results were considered together with Ca^{2+} , Mg^{2+} , HCO_3^- , and Na^+ concentrations for assessing the potential sodicity hazard of the coastal water resources.

Bicarbonates

The data pertaining to HCO_3^- concentration are presented in Table 3. The bicarbonate concentration in the water samples ranged from 0.20 to 0.90 meq L^{-1} , with a mean value of 0.40 meq L^{-1} , during the pre-monsoon season and from 0.10 to 0.50 meq L^{-1} , with a mean value of 0.25 meq L^{-1} , during the post-monsoon season. The corresponding standard deviations were 0.17 and 0.11 meq L^{-1} , while the coefficients of variation were 42.58% and 45.66%, respectively. The relatively higher mean HCO_3^- concentration during the pre-monsoon season indicates greater concentration of dissolved carbonate species under comparatively dry conditions.

The occurrence of HCO_3^- in groundwater is primarily associated with the dissolution and weathering of carbonate minerals and the interaction of groundwater with carbonic acid. Carbon dioxide dissolved in water forms carbonic acid, which promotes the weathering of carbonate-bearing minerals and contributes to bicarbonate formation. The dissolution of calcite and dolomite within the aquifer can therefore enrich groundwater with HCO_3^- . Bicarbonate may also originate from the weathering of silicate minerals through interactions between groundwater and aluminosilicate minerals [36]. The relatively higher bicarbonate concentration during the pre-monsoon season may be related to enhanced evaporation, longer groundwater residence time, and reduced dilution, whereas monsoonal recharge may have reduced concentrations during the post-monsoon season.

The observed variations in bicarbonate concentration are comparable with the findings reported by Satyavan *et al.* [34] and Bharadwaj *et al.* [35]. The presence and concentration of HCO_3^-

are particularly important for irrigation-water assessment because bicarbonate can participate in precipitation reactions involving Ca^{2+} and Mg^{2+} , thereby influencing the relative abundance of Na^+ in irrigation water and contributing to the calculation of residual sodium carbonate (RSC).

Chlorides

The Cl^- concentration in the water samples ranged from 1.10 to 216.10 meq L^{-1} during the pre-monsoon season and from 0.70 to 181.30 meq L^{-1} during the post-monsoon season (Table 3). The mean Cl^- concentration was 24.73 meq L^{-1} during the pre-monsoon season and 20.16 meq L^{-1} during the post-monsoon season. The corresponding standard deviations were 42.18 and 34.77 meq L^{-1} , while the coefficients of variation were 170.51% and 172.50%, respectively. The high coefficients of variation indicate substantial spatial variability in chloride concentrations across the study area.

The distribution of water samples according to chloride concentration showed that, during the pre-monsoon season, 45.10% of the samples were within the <4.0 meq L^{-1} category, generally considered safe for most plants. Another 45.10% of the samples had Cl^- concentrations >10 meq L^{-1} , indicating a potential risk of severe chloride-related problems, while 9.80% fell within the 4.0-10.0 meq L^{-1} category, where injury may occur in moderately sensitive plants. During the post-monsoon season, 58.82% of the samples were in the <4.0 meq L^{-1} category, 37.26% were >10 meq L^{-1} , and 3.92% were within the 4.0-10.0 meq L^{-1} category (Table 4).

The relatively high chloride concentrations observed at several locations may be associated with the coastal setting and seawater intrusion, together with mineral dissolution and localized anthropogenic inputs. Chloride is highly mobile in groundwater and is generally considered a useful indicator of salinization and seawater mixing in coastal aquifers. The higher mean Cl^- concentration during the pre-monsoon season may be related to reduced freshwater recharge, increased evaporation, and greater influence of saline water during the dry period. Conversely, monsoonal recharge can dilute dissolved chloride concentrations, resulting in the lower mean observed during the post-monsoon season.

The high spatial variability in Cl^- concentration suggests that the influence of salinity is not uniform throughout the study area. Coastal locations are likely to experience a stronger marine influence, whereas variations in inland or highland locations may reflect differences in recharge, groundwater flow, mineralization, land use, and localized anthropogenic inputs. Chloride concentrations therefore provide an important indicator of the spatial extent and seasonal variation of salinity in the coastal aquifer.

From an irrigation perspective, excessive chloride can adversely affect plants through osmotic stress and specific-ion toxicity, particularly when chloride accumulates in the root zone or is absorbed through plant roots and leaves. Chloride toxicity is therefore dependent not only on its concentration in irrigation water but also on crop tolerance, soil conditions, irrigation method, drainage, and exposure duration. The observed results are in agreement with the findings of Mahmud *et al.* [28] and Alzubi [37]. Similar concerns regarding chloride-related irrigation hazards have also been reported by previous studies [24, 25, 38, 39].

Overall, the relatively high chloride concentrations recorded at several sampling locations, particularly during the pre-monsoon season, indicate the need for regular monitoring of coastal groundwater salinity and appropriate irrigation-water management to minimize the risk of salt accumulation and

chloride toxicity in agricultural soils.

Sulphates

The results for SO_4^{2-} concentration are presented in Table 3. The SO_4^{2-} concentration in the water samples ranged from 0.18 to 4.94 meq L^{-1} , with a mean value of 1.47 meq L^{-1} , during the pre-monsoon season. During the post-monsoon season, SO_4^{2-} concentration ranged from 0.07 to 3.76 meq L^{-1} , with a mean value of 0.70 meq L^{-1} . The corresponding standard deviations were 1.69 and 0.93 meq L^{-1} , while the coefficients of variation were 115.43% and 132.00%, respectively. The high coefficients of variation indicate considerable spatial variability in sulphate concentration across the study area.

The distribution of water samples according to SO_4^{2-} concentration showed that, during the pre-monsoon season, 84.31% of the samples belonged to the <4.0 meq L^{-1} category, representing low sulphate concentration, while 15.69% fell within the 4.0-12.0 meq L^{-1} category. During the post-monsoon season, 100% of the samples were classified within the <4.0 meq L^{-1} category (Table 5). Thus, sulphate concentrations were generally low in the study area, although a small proportion of samples exhibited comparatively elevated concentrations during the pre-monsoon season.

Sulphate in groundwater may originate from both natural geochemical processes and anthropogenic activities. The dissolution and weathering of sulphate-bearing minerals can release SO_4^{2-} into groundwater, while oxidation of sulphide minerals may provide an additional source. Agricultural activities may also contribute sulphate through the application of sulphate-containing fertilizers and soil amendments. The concentration of SO_4^{2-} in groundwater can subsequently be modified by mineral dissolution, precipitation, adsorption, microbial transformations, and groundwater-rock interactions as water moves through the aquifer [40]. The relatively higher mean SO_4^{2-} concentration during the pre-monsoon season may be associated with increased evaporation, longer residence time, and reduced dilution, whereas monsoonal recharge may have contributed to the lower concentrations observed during the post-monsoon season.

Among the major anions, Cl^- was the dominant ion, followed by SO_4^{2-} , HCO_3^- , and CO_3^{2-} . The relative abundance of anions in the irrigation water was therefore generally in the order $\text{Cl}^- > \text{SO}_4^{2-} > \text{HCO}_3^- > \text{CO}_3^{2-}$, consistent with the observations of Rajput and Polara [30]. Similar predominance of chloride among the major anions has been reported by Mahmud *et al.* [28] and Mustapha *et al.* [29].

The predominance of Cl^- over the other anions, together with the occurrence of Na-Cl water types, particularly during the pre-monsoon season, suggests a possible influence of seawater mixing or seawater intrusion in portions of the coastal aquifer. The major water types occurred predominantly in the order $\text{NaCl} > \text{CaMgCl} > \text{CaHCO}_3$, indicating the influence of both marine sources and water-rock interaction on groundwater chemistry. The greater influence of saline water during the pre-monsoon season may be related to reduced freshwater recharge, increased groundwater abstraction, and a consequent reduction in the hydraulic gradient toward the sea [22]. Similar groundwater facies have been reported by Manikandan *et al.* [41].

The higher chloride concentration observed during the pre-monsoon season further supports the possibility of enhanced salinity during the dry period. The mean Cl^- concentration was 24.73 meq L^{-1} during the pre-monsoon season and 20.16 meq L^{-1} during the post-monsoon season (Table 3). The predominance of chloride and the elevated $\text{Cl}^-/\text{SO}_4^{2-}$ ratio at

several sampling locations may indicate a stronger marine influence because chloride is a major constituent of seawater. However, the $\text{Cl}^-/\text{SO}_4^{2-}$ ratio should be interpreted together with EC, Na^+ , Mg^{2+} , Ca^{2+} , and other hydrochemical indicators rather than used as a standalone indicator of seawater intrusion.

Overall, the ionic composition of the water samples, particularly the dominance of Na^+ and Cl^- , indicates that salinity and possible seawater influence are important factors controlling the hydrochemical characteristics of the coastal water resources in the study area. These findings highlight the need for continued monitoring of chloride, electrical conductivity, and major-ion ratios to assess seasonal changes in groundwater quality and irrigation suitability.

Chemical Parameters of Water Samples Collected from the Study Area during Pre- and Post-Monsoon Seasons

The water samples collected from the study area were analyzed for various chemical parameters to assess their quality and suitability for irrigation. The results of the different chemical quality parameters are presented in Table 6 and discussed in the following sections.

pH of Irrigation Water ($\text{pH}_{\text{i,w}}$)

The pH of irrigation water ($\text{pH}_{\text{i,w}}$) showed considerable variation between the pre- and post-monsoon seasons. During the pre-monsoon season, $\text{pH}_{\text{i,w}}$ values ranged from 5.75 to 8.44, with a mean value of 7.29. In the post-monsoon season, the values ranged from 5.60 to 7.97, with a mean of 6.93. The standard deviations were 0.53 and 0.44, while the corresponding coefficients of variation were 7.24% and 6.40% for the pre- and post-monsoon seasons, respectively (Table 6). The relatively low coefficients of variation indicate that pH showed comparatively limited spatial variability across the study area.

The seasonal distribution of water samples according to $\text{pH}_{\text{i,w}}$ categories showed that, during the pre-monsoon season, the highest proportion of samples (52.94%) occurred within the 6.5-7.3 range, classified as neutral. This was followed by samples in the 7.3-7.8 range (29.41%), indicating slightly alkaline conditions. About 13.73% of the samples fell within the 7.8-8.4 range, representing moderately alkaline conditions, while 1.96% each were recorded in the 6.0-6.5 and 5.5-6.0 categories, corresponding to slightly acidic and moderately acidic conditions, respectively.

Overall, the predominance of samples within the neutral to slightly alkaline range indicates that the pH of most water samples was generally favorable for irrigation. The relatively higher mean pH during the pre-monsoon season may be associated with increased evaporation, concentration of dissolved constituents, and greater interaction between groundwater and carbonate-bearing minerals during the relatively dry period. In contrast, the lower mean pH observed during the post-monsoon season may reflect the influence of monsoonal recharge and dilution of dissolved ions. However, the observed seasonal differences were relatively small, indicating that pH remained comparatively stable across the study area.

The distribution of pH also suggests that localized acidic or alkaline conditions occur at some sampling locations. Such variations may result from differences in lithology, groundwater residence time, mineral dissolution, organic matter decomposition, and localized anthropogenic inputs. Therefore, although pH alone did not indicate a major limitation for most samples, its interaction with other chemical parameters should be considered when evaluating the overall irrigation-water

season. Similar to pre-monsoon season, the maximum percent of samples *i.e.*, 70.59, 15.69, 1.96, 7.84 and 3.92 per cent were in the category of 6.5-7.3 (neutral), 7.3-7.8 (slightly alkaline), 7.8-

8.4 (moderately alkaline), 6.0-6.5 (slightly acid) and 5.5-6.0 (moderately acid) at post-monsoon season respectively (Table 7) quality of the coastal aquifer system.

Table 2: Concentration of cations of water samples collected from Study area (n = 102)

Descriptive statistics	Ca ²⁺		Mg ²⁺		Na ⁺		K ⁺	
	(meq L ⁻¹)							
	Pre-monsoon	Post-monsoon	Pre-monsoon	Post-monsoon	Pre-monsoon	Post-monsoon	Pre-monsoon	Post-monsoon
Minimum	0.70	0.50	0.60	0.20	0.13	0.07	0.01	0.01
Maximum	21.90	18.90	79.80	72.60	87.56	80.34	16.55	12.63
Mean	5.24	3.85	12.51	10.43	14.85	12.44	2.75	2.05
Standard deviation	5.95	4.87	17.73	16.80	24.70	20.54	4.62	3.67
Coefficient of variation (%)	113.49	127.0	141.76	161.0	166.32	165.14	168.17	179.10

Table 3: Concentration of anions of water samples collected from Study area (n = 102)

Descriptive statistics	CO ₃ ⁻²		HCO ₃ ⁻		Cl ⁻¹		SO ₄ ⁻²		B	
	(meq L ⁻¹)									
	Pre-monsoon	Post-monsoon	Pre-monsoon	Post-monsoon	Pre-monsoon	Post-monsoon	Pre-monsoon	Post-monsoon	Pre-monsoon	Post-monsoon
Minimum	0.10	0.10	0.20	0.1	1.10	0.7	0.18	0.07	0.70	0.40
Maximum	0.70	0.50	0.90	0.5	216.10	181.30	4.94	3.76	94.32	89.90
Mean	0.32	0.23	0.40	0.25	24.73	20.16	1.47	0.70	18.18	15.40
Standard deviation	0.14	0.10	0.17	0.11	42.18	34.77	1.69	0.93	23.79	22.54
Coefficient of variation (%)	44.26	42.24	42.58	45.66	170.51	172.50	115.43	132.0	130.86	146.40

Table 4: Percent distribution of water samples for different ratings of chloride content of Study area

Particulars				
Sl. No	Chloride Classes	Range (meq L ⁻¹)	Pre-monsoon	Post-monsoon
1	Generally safe for all plants	<4.0	45.10 (23, 1.75 meq L ⁻¹)	58.82 (30, 1.43 meq L ⁻¹)
2	Moderately tolerant plants show injury	4.0-10.0	9.80 (5, 7.34 meq L ⁻¹)	3.92 (2, 7.35 meq L ⁻¹)
3	Can cause severe problems	>10.0	45.10 (23, 51.50 meq L ⁻¹)	37.26 (19, 51.07 meq L ⁻¹)

Note: Values in parenthesis indicates number of samples and mean values of respective classes, respectively. (Mass, 1990)

Table 5: Percent distribution of water samples with respect to different ratings of sulphate content of Study area

Particulars				
Sl. No	Sulphate Classes	Range (meq L ⁻¹)	Pre-monsoon	Post-monsoon
1	Low	<4.0	84.31 (43, 0.90 meq L ⁻¹)	100 (51, 0.70 meq L ⁻¹)
2	Medium	4.0-12.0	15.69 (8, 4.53 meq L ⁻¹)	0
3	High	>12.0	0	0

Note: Values in parenthesis indicates number of samples and mean values of respective classes, respectively. (Ayer and Westcott, 1985)

The acidity or alkalinity of groundwater is primarily governed by the activity of hydrogen ions (H⁺) in solution. The pH of irrigation water (pH_w) is an important indicator of the chemical environment of groundwater and reflects the influence of dissolved minerals, carbonate-bicarbonate equilibria, and other geochemical processes. The results showed that the water samples ranged from moderately acidic to moderately alkaline during both seasons. The relatively higher pH values observed at some locations may be associated with the presence of carbonate and bicarbonate ions and the contribution of base cations, particularly Na⁺, which can influence the carbonate equilibrium of groundwater. Samples with pH values exceeding 8.0 indicate localized alkaline conditions, which may be associated with increased concentrations of bicarbonate and carbonate ions and enhanced interaction with alkaline minerals.

The lower pH values recorded at some sampling locations may be attributed to prolonged water-rock interaction, weathering of aquifer materials, and the presence of acidic constituents generated during the decomposition of organic matter. Limited availability of alkaline minerals or base-forming constituents may further contribute to the development of relatively acidic

groundwater conditions [42]. Similar observations were reported by Kabaria [43] in Amreli District of Gujarat and Verma *et al.* [23] in Churu District, Rajasthan. The occurrence of slightly alkaline groundwater may also be related to the dissolution of carbonate-bearing minerals and the presence of exchangeable base cations in the aquifer system [44]. Overall, the relatively narrow range of pH values and low coefficients of variation indicate that pH was comparatively stable across the study area, although localized acidic and alkaline conditions were evident.

Electrical Conductivity (EC_w)

The electrical conductivity of irrigation water (EC_w) exhibited substantial spatial and seasonal variation across the study area. During the pre-monsoon season, EC_w ranged from 0.13 to 58.90 dS m⁻¹, with a mean value of 8.80 dS m⁻¹. During the post-monsoon season, the values ranged from 0.11 to 32.90 dS m⁻¹, with a mean value of 5.26 dS m⁻¹. The corresponding standard deviations were 14.85 and 8.33 dS m⁻¹, while the coefficients of variation were 168.72% and 158.17%, respectively (Table 6). The high coefficients of variation indicate pronounced spatial variability in the concentration of

dissolved salts across the study area.

The distribution of water samples according to EC_{iw} classes showed that, during the pre-monsoon season, the highest proportion of samples (31.38%) occurred in the >4.0 dS m^{-1} category, classified as unsuitable for irrigation. This was followed by samples in the $0.75-2.25$ dS m^{-1} category (29.41%), classified as permissible, and the $0.25-0.75$ dS m^{-1} category (29.41%), classified as good. Approximately 7.84% of the samples were in the <0.25 dS m^{-1} category, classified as excellent, while 1.96% fell within the $2.25-4.0$ dS m^{-1} category, classified as doubtful.

During the post-monsoon season, the largest proportion of samples (35.29%) occurred in the $0.75-2.25$ dS m^{-1} category, followed by 29.42% in the >4.0 dS m^{-1} category, 23.53% in the $0.25-0.75$ dS m^{-1} category, and 11.76% in the <0.25 dS m^{-1} category (Table 8). No samples were reported in the $2.25-4.0$ dS m^{-1} category during the post-monsoon season.

The spatial distribution of EC_{iw} showed a clear relationship with proximity to the coastline. Higher EC_{iw} values were generally recorded in samples collected close to the sea, whereas relatively lower values occurred at locations farther inland. This pattern indicates the possible influence of marine salinity, seawater mixing or intrusion, evaporation, and accumulation of dissolved salts in the coastal aquifer. The particularly high EC values observed at some coastal locations suggest localized salinization and warrant further assessment using complementary hydrochemical indicators such as Cl^{-}/Br^{-} ratios, Na^{+}/Cl^{-} ratios, major-ion facies, and hydrochemical indices where appropriate.

The mean EC_{iw} was substantially higher during the pre-monsoon season (8.80 dS m^{-1}) than during the post-monsoon season (5.26 dS m^{-1}). The higher pre-monsoon EC may be attributed to increased evaporation, reduced freshwater recharge, longer groundwater residence time, and concentration of dissolved salts. In contrast, the lower EC during the post-monsoon season is consistent with monsoonal recharge and dilution of soluble salts in the groundwater system [45]. Similar seasonal behavior has been associated with evaporation-driven concentration during dry periods and rainfall-induced dilution during wet periods [41].

Overall, EC_{iw} represents one of the major limitations affecting irrigation-water quality in the study area. The high variability and elevated EC values, particularly at coastal locations, indicate that salinity is an important factor controlling the suitability of groundwater and other water resources for irrigation. Consequently, EC should be evaluated together with SAR, RSC, chloride concentration, and other relevant parameters when assessing the overall irrigation suitability of the sampled waters.

Sodium Adsorption Ratio (SAR)

The data presented in Table 6, showed that the sodium adsorption ratio of water samples in the study area for both pre- and post-monsoon season ranged from 0.07 to 18.93 and from 0.06 to 25.22, respectively. The average value of the sodium adsorption ratio was higher in pre-monsoon season (3.54)

compared to post-monsoon season (3.36). The standard deviation and co-efficient of variation for pre-monsoon season were 5.12 and 144.58 per cent, respectively. In the case of post-monsoon season standard deviation and co-efficient of variation were 5.27 and 156.77 per cent, respectively. The per cent distribution of water samples under different categories of SAR of irrigation water revealed that, the highest per cent of samples (80.39) were in the range of SAR <10 (safe), followed by 10-18 (moderately safe) (17.65 per cent) and 18-26 (moderately unsafe) (1.96 per cent) at pre-monsoon season. Similar to pre-monsoon season, maximum per cent of samples i.e., 86.27, 11.76 and 1.96 per cent were in the category of <10 (safe), 10-18 (moderately safe) and 18-26 (moderately unsafe) at post-monsoon season respectively (Table 9).

SAR (Sodium Adsorption Ratio) is a parameter used to assess the quality of irrigation water, specifically its suitability for agricultural use. It is determined based on the concentrations of sodium and other key alkaline and alkaline earth cations present in groundwater. The lower SAR values in the study area are attributed to the relatively lower concentration of sodium compared to calcium and magnesium. In contrast, higher SAR values result from increased dispersion of organic matter and clay particles, coupled with elevated sodium content in groundwater samples, leading to an increase in sodium adsorption ratio. Similar reports were also obtained by Hannan *et al.* [46] and Ashraf *et al.* [47]. A high sodium adsorption ratio in water samples indicates a risk of sodium (alkali) displacing calcium (Ca^{2+}) and magnesium (Mg^{2+}) in the soil through cation exchange. This process can lead to detrimental effects on soil structure, such as reduced permeability, which in turn affects soil fertility and diminishes crop yields [48]. The rise in sodium adsorption ratio values in water samples correlates with increasing pH and electrical conductivity (EC) of groundwater, likely due to the prevalence of soluble Na^{+} ions outweighing Ca^{2+} and Mg^{2+} ions [44].

Residual sodium carbonate (RSC)

The results of residual sodium carbonate of water samples collected from the study area are presented in Table 6. It was observed from the data that residual sodium carbonate of water samples collected from pre-monsoon season ranged from -96.8 to -0.70 meq L^{-1} with a mean value of -16.82 meq L^{-1} , while in post-monsoon, it ranged from -85.6 to -0.40 meq L^{-1} with a mean value of -13.80 meq L^{-1} . The standard deviation and co-efficient of variation were 22.85 meq L^{-1} and -135.83 per cent, respectively during pre-monsoon. The corresponding values were 21.14 meq L^{-1} and -153.0 per cent, respectively during post-monsoon. The per cent distribution of water samples under different categories of RSC of irrigation water revealed that, 100 per cent of samples from pre- and post-monsoon season comes under the category of safe (<1.25 meq L^{-1}) (Table 10). Residual sodium carbonate is a common means of assessing the sodium permeability hazard and takes into account.

Table 6: Descriptive statistics of pH_{iw} , EC_{iw} , SAR and RSC of water samples collected from the study area

Descriptive statistics	pH_{iw}		EC_{iw} (dS m^{-1})		SAR		RSC	
	Pre-monsoon	Post-monsoon	Pre-monsoon	Post-monsoon	Pre-monsoon	Post-monsoon	Pre-monsoon	Post-monsoon
Minimum	5.75	5.60	0.13	0.11	0.07	0.06	-96.80	-85.6
Maximum	8.44	7.97	58.90	32.90	18.93	25.22	-0.70	-0.40
Mean	7.29	6.93	8.80	5.26	3.54	3.36	-16.82	-13.80
Standard deviation	0.53	0.44	14.85	8.33	5.12	5.27	22.85	21.14
Coefficient of variation (%)	7.24	6.40	168.72	158.17	144.58	156.77	-135.83	-153.0

Table 7: Percent distribution of water samples concerning different ratings of water pH_{iw} content of Study area

Particulars				
Sl. No	pH _{iw} Classes	Range	Pre-monsoon	Post-monsoon
1	Moderately acid	5.5-6.0	1.96 (1, 5.75)	3.92 (2, 5.47)
2	Slightly acid	6.0-6.5	1.96 (1, 6.40)	7.84 (4, 6.25)
3	Neutral	6.5-7.3	52.94 (27, 6.98)	70.59 (36, 6.92)
4	Slightly alkaline	7.3-7.8	29.41 (15, 7.6)	15.69 (8, 7.48)
5	Moderately alkaline	7.8-8.4	13.73 (7, 8.13)	1.96 (1, 7.97)

Note: Values in parenthesis indicates number of samples and mean values of respective classes respectively. (Richards, 1954)

Table 8: Percent distribution of water samples with respect to different ratings of water EC_{iw} content of Study area

Particulars				
Sl. No	EC _{iw} Classes	Range (dS m ⁻¹)	Pre-monsoon	Post-monsoon
1	Excellent	<0.25	7.84 (4, 0.19 dS m ⁻¹)	11.76 (6, 0.16 dS m ⁻¹)
2	Good	0.25 to 0.75	29.41 (15, 0.51 dS m ⁻¹)	23.53 (12, 0.53 dS m ⁻¹)
3	Permissible	0.75 to 2.25	29.41 (15, 1.11 dS m ⁻¹)	35.29 (18, 1.07 dS m ⁻¹)
4	Doubtful	2.25 to 4.00	1.96 (1, 3.21 dS m ⁻¹)	0
5	Unsuitable	>4.00	31.38 (16, 26.29 dS m ⁻¹)	29.42 (15, 16.14 dS m ⁻¹)

Note: Values in parenthesis indicates number of samples and mean values of respective classes respectively. (Richards, 1954)

Table 9: Percent distribution of water samples with respect to different ratings of SAR content of Study area

Particulars				
Sl. No	SAR Classes	Range	Pre-monsoon	Post-monsoon
1	Safe	<10	80.39 (41, 1.27)	86.27 (44, 1.68)
2	Moderately safe	10-18	17.65 (9, 12.21)	11.76 (6, 12.04)
3	Moderately unsafe	18-26	1.96 (1, 18.93)	1.96 (1, 25.22)
4	Unsafe	>26	0	0

Note: Values in parenthesis indicates number of samples and mean values of respective classes respectively. (Richards, 1954)

Table 10: Percent distribution of water samples with respect to different ratings of RSC content of Study area

Particulars				
Sl. No	RSC Classes	Range (meq L ⁻¹)	Pre-monsoon	Post-monsoon
1	Suitable	<1.25	100 (51, -16.82 meq L ⁻¹)	100 (51, -13.80 meq L ⁻¹)
2	Marginal	1.25-2.5	0	0
3	Unsuitable	>2.50	0	0

Note: Values in parenthesis indicates number of samples and mean values of respective classes respectively. (Eaton, 2002)

Table 11: Overall water quality classification of pre- and post-monsoon season water samples as per the guidelines of CSSRI, Karnal

Sl. No	Water quality classes	Water quality parameters				
		EC _{iw} (dSm ⁻¹)	SAR	RSC (meq L ⁻¹)	Total number of samples (51)	
					Pre-monsoon	Post-monsoon
1	Good	<2.0	<10	<2.5	34 (66.67%)	33 (64.71%)
2	Marginally saline	2.0-4.0	<10	<2.5	2 (3.92%)	2 (3.92%)
3	Saline	>4.0	<10	<2.5	6 (11.76%)	9 (17.65%)
4	High SAR saline	>4.0	>10	<2.5	10 (19.61%)	7 (13.73%)
5	Marginally alkali	<4.0	<10	2.5-4.0	-	-
6	Alkali	<4.0	<10	>4.0	-	-
7	Highly alkali	<4.0	>10	>4.0	-	-

The bicarbonate or carbonate and calcium or magnesium concentrations in groundwater. A negative value indicates little risk of sodium accumulation due to offsetting levels of calcium and magnesium. Similar result was also reported by Lai *et al.* [49] and Mahmud *et al.* [28].

3.2.5 Classification of water samples based on CSSRI, Karnal

Overall water quality classification as per the guidelines of CSSRI, Karnal revealed that, in pre-monsoon season, 66.67, 19.61, 11.76 and 3.92 per cent of water samples comes under the category of good, high SAR saline, saline and marginally saline, respectively. Similarly in post-monsoon season, 64.71, 17.65, 13.73 and 3.92 per cent of samples comes under the category of good, saline, high SAR saline and marginally saline,

respectively (Table 11). A similar result was also reported by Vishwanath *et al.* [24]; Ramprakash *et al.* [25] and Hebsur *et al.* [50].

Conclusion

Based on the results of the present investigation, it can be concluded that salinity is an important constraint affecting the irrigation suitability of water resources in the study area. Approximately 31.37% and 29.41% of the water samples during the pre- and post-monsoon seasons, respectively, recorded EC_{iw} > 4.0 dS m⁻¹, indicating that these samples were unsuitable for irrigation according to the adopted classification criteria. The lower EC_{iw} values observed during the post-monsoon season may be attributed primarily to the dilution of soluble salts resulting from monsoonal recharge.

According to the CSSRI, Karnal classification, 11.76% and 19.61% of the pre-monsoon samples and 17.65% and 13.73% of the post-monsoon samples were classified as saline and higher SAR saline, respectively. These findings indicate that a considerable proportion of the sampled water resources require careful management before use for irrigation. Their efficient and sustainable utilization requires regular monitoring of water quality, along with consideration of rainfall patterns, soil characteristics, crop selection, irrigation practices, drainage conditions, and nutrient management. Integrated management of these factors is essential for minimizing salinity and sodicity hazards and maintaining sustainable agricultural production in the coastal region.

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