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# Comprehensive Analysis of Groundwater Suitability for Irrigation in Rural Hyderabad, Sindh, Pakistan

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**Abstract:** An irrigation quality assessment for rural Hyderabad was made by determining the pH, EC, TDS and TH beside major cations and anions. This study employed various parameters to determine the suitability of groundwater for irrigation and its hydrochemistry. Permissible limits of major cations and anions revealed that approximately 26% of samples exceeded acceptable levels for Electrical Conductivity (EC), 87% for $Ca^{2+}$, 89% for $Mg^{2+}$, and 60% for $Na^{+}$, while none exceeded the limits for $K^{+}$. Conversely, 47% of samples for $HCO_3^{-}$, 91% for $Cl^{-}$, and 100% for $SO_4^{2-}$, $NO_3^{-}$, and $CO_3^{2-}$ proved suitability for irrigation. Notably, irrigation indices highlighted favorable results, with 100% conformity for *SAR*, *SSP*, *RSP*, and *PI* values, and substantial percentages of 78% and 85% for *MH* and *KR* values, respectively, affirming their suitability for irrigation practices. Employing the USSL diagram, 22%, 65%, and 11% of samples fall into the C2S1, C3S1, and C4S1 categories. According to the Wilcox diagram, 25%, 43%, 30%, and 2% are classified under C1, C2, C3, and C4 categories, respectively. The Gibbs ratio shows a concentration within the evaporation dominance, and *CAI* values showed positive ion exchange. Overall, Hyderabad's rural areas are generally suitable for irrigation, apart from certain areas where water quality may not be acceptable for plants lacking high salt tolerance.

**Keywords:** irrigation quality; groundwater quality assessment; USSL diagram; chloralkaline index; permeability index; Kelley's ratio; soluble sodium percentage



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## 1. Introduction

The chemical composition of water is a crucial factor to assess before its use for domestic or irrigation purposes [1]. Groundwater holds the potential to serve as Pakistan's most dependable water source [2]. The productivity of fields and crops is influenced by the quality of water used in irrigation [3–5]. Evaluating the quality of irrigation water is crucial for developing a sustainable, long-term strategy for managing crop yields [6], since high Electrical Conductivity in water prevents plants from successfully competing with ions present in the soil solution [7,8]. Plant growth is affected to varying degrees by the salt content in irrigation water at different stages of growth [9]; therefore, the deteriorating quality of groundwater for irrigation has become a growing concern in recent times [10].

The suitability of groundwater for irrigation can be related to its complex hydrogeological characteristics and natural and anthropogenic contaminants. Even though the anthropogenic pressure is increasing in the groundwater, in some cases natural pollutants are occurring [11]. The quality of groundwater is mainly influenced by over chemical fertilization [12–17], a hydrogeochemical process in aquifers [18–21], precipitation [22–24], land use and cover [25–27], and mining activities [28]. Apart from these, one of the major reasons for this contamination is improper irrigations from canals containing urban and industrial effluent and poor drainage [29,30]. As a conclusive result, it becomes necessary to perform irrigation water quality tests to achieve higher yields and increase crop water productivity [31,32].

Rural Hyderabad is among the famous cultivated areas in the production of Cash Crops in the Sindh Province of Pakistan. Groundwater is one of the most important sources for irrigation after the use of surface water in the area. An effort is made in the present paper to determine the physiochemical properties of groundwater and its suitability for eleven Union Councils (UC's) of the Rural Hyderabad District of the Sindh Province of Pakistan. A total of 44 samples were collected, with 4 from each UC, to obtain averaged results. The conclusions drawn from this research may supply crucial insights for local governance and serve as a foundational resource for researchers aiming to gather essential information about the region.

## 2. Materials and Methods

### *2.1. Study Area Description*

The district of Hyderabad occupies 993 km$^2$ and is situated at latitude 25.367° N and longitude 68.367° E. It has an elevation of thirteen meters. The provincial capital of Karachi is around 150 km (93 miles) from the area, which is situated on the east bank of the Indus River. The districts of Tando Muhammad Khan on the east and south, Tando Allahyar on the east, Matiari on the north, Jamshoro on the northwest, and Thatta on the southwest encircle this district. This district is bordered on the west by the Indus River, as illustrated in Figure 1. These areas are under high influence of groundwater irrigation during shortages of water [33].

### *2.2. Sampling and Measurements*

Using hand pumps and tubewells, a total of 44 samples were taken in the pre-monsoon season of 2022, covering various Union Council regions and depths. The coordinates of the samples were recorded using a coordination device. To ensure the collection of accurate and representative data, we meticulously gathered 44 water samples. Two 1000 mL glass jars and a 2.5 L white plastic bottle that had been previously cleaned were used to gather each water sample. All containers were thoroughly cleaned with the water to be collected before sampling. Each sample was stored and preserved with utmost care, with diligent attention paid to recording the temperature at the time of collection. The bottles were arranged for analysis after each sample was given a thorough label. All coordinates are recorded at the sample time in accordance with Figure 1. We forwarded the samples to the Department of Land and Water Management Laboratory at Sindh Agriculture University, Tandojam, Pakistan, and the Drainage and Reclamation Institute (DRIP) in Tandojam once they had been preserved. We compared the results of the analysis with standard guidelines to understand the current condition of the water.

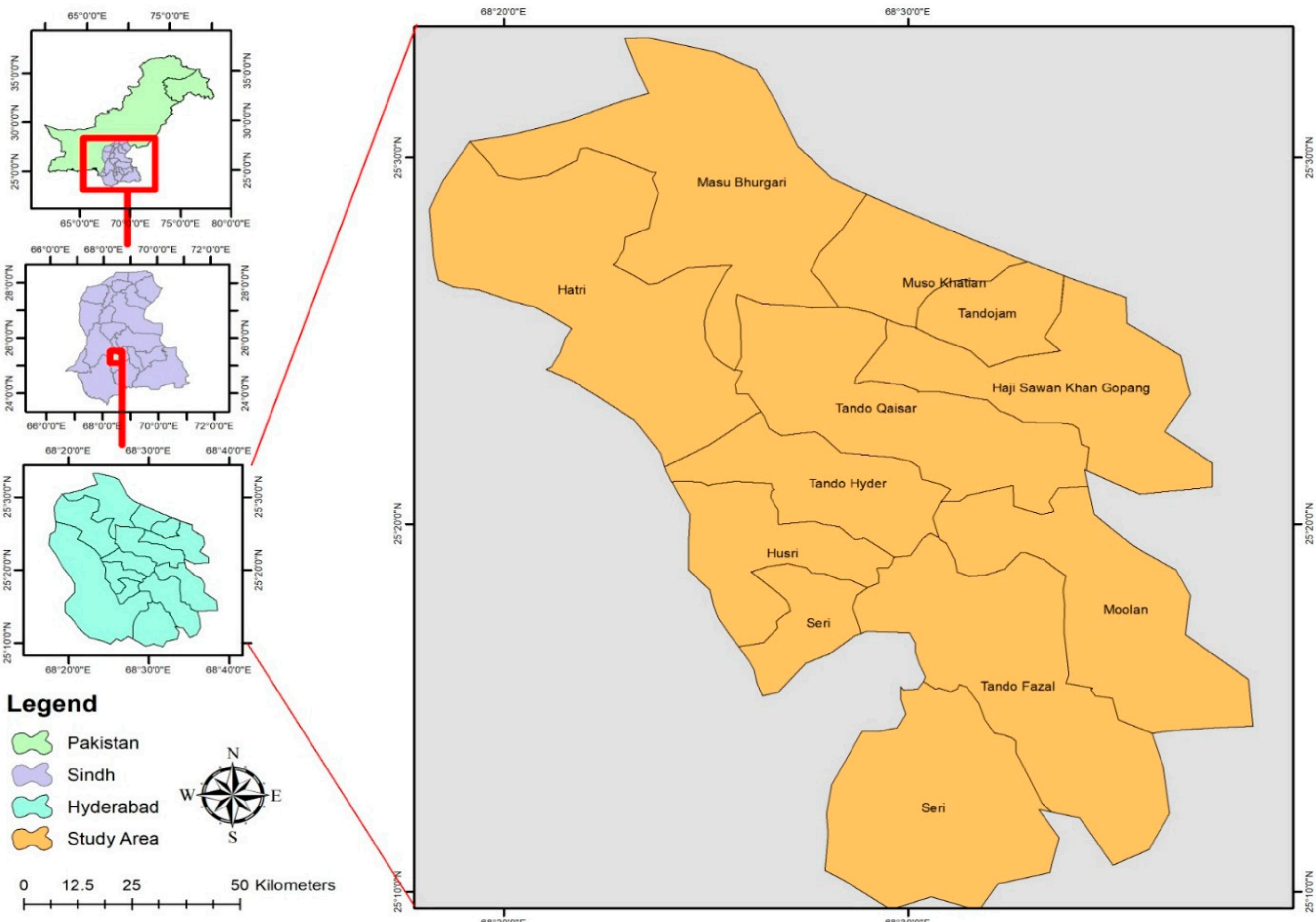



**Figure 1.** Location map of the study area encompasses eleven Village Councils (VCs), also designated as Union Councils (UC's) in Pakistan; they go by the names UC Moosa Khatian, UC Tando Fazal, UC Tando Hyder, UC Moosa Khatian, UC Hatri, UC Seri, UC Massu Bhurgri, UC Tando Qaisar, UC Moolan, UC Sawan Gopang, and UC Hoosri.

### *2.3. Chemical Parameters of the Samples*

The evaluation of hydrogen ion concentration (pH) and Electrical Conductivity (EC) was conducted using digital meters (Orion Star A216 TFS Instrumemts, USA) and (DCM-900, Global make, USA) dedicated to pH and EC measurements. To ensure the removal of total suspended solids, a filter with the pore size of 0.45 µm was used for the filtration of the sample. The determination of sulphate ($SO_4^{2-}$) content was conducted through the UV spectrophotometric method (MODEL), while the quantification of chloride ($Cl^-$) and bicarbonate ($HCO_3^-$) content employed the titration method. Detection of $Ca^{2+}$, $Mg^{2+}$, and Total Hardness (TH) was conducted using the titration method, while sodium ($Na^+$) and potassium ($K^+$) were estimated through the flame photometer method [34].

### *2.4. Irrigation Water Quality*

Several irrigation water quality parameters were calculated using the measurements that were collected. These included the Magnesium Hazard, Residual Sodium Carbonate, the Sodium Adsorption Ratio, the Permeability Index, and the Chloralkaline Index. These computations were used to assess the irrigation-quality groundwater. Additionally, Drawer (3.0) and Aquachem (11.0) software were used to generate diagrams such as the Gibbs diagrams I and II, the Wilcox Permeability Index, and the salinity of the United States Salinity Laboratory (USSL) diagram. In a similar vein, GW-chart software (2.0) was used to produce the Piper Diagram.

### 2.5. Sodium Hazard (SH)

*SH* values were figured out by assessing the *SSP* and *SAR*, and by constructing the Wilcox diagram.

#### 2.5.1. Soluble Sodium Percentage (SSP) or (%Na)

*SSP* or *%NA* was determined using the equation already discussed in [35–37]. The ionic concentration was expressed in (meq/L), as shown in Equation (1).

$$SSP = \frac{Na^{+} + K^{+}}{\left(Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}\right)} \times 100 \quad (1)$$

#### 2.5.2. Sodium Absorption Ratio (SAR)

*SAR* was calculated using the equation employed by equation [38]. The ionic concentration was presented in (meq/L), as shown in Equation (2).

$$SAR = \frac{Na^{+}}{\sqrt{\left(Ca^{2+} + Mg^{2+}\right)/2}} \quad (2)$$

### 2.6. Residual Sodium Carbonate (RSC)

*RSC* was calculated using the equation provided by [39], as provided in Equation (3).

$$RSC = \left(HCO_3^{-} + CO_3^{2-}\right) - \left(Ca^{2+} + Mg^{2+}\right) \quad (3)$$

### 2.7. Magnesium Hazard (MH)

*MH* was evaluated by the formula given by [40]. The concentration of cations was expressed in (meq/L), as shown in Equation (4).

$$MH = \frac{Mg^{2+}}{\left(Ca^{2+} + Mg^{2+}\right)} \times 100 \quad (4)$$

### 2.8. Permeability Index (PI)

*PI* was calculated using the formula provided by [41]. All ion concentrations were considered in (meq/L), as shown in Equation (5).

$$PI = \frac{Na^{+} + \sqrt{HCO_3^{-}}}{\left(Ca^{2+} + Mg^{2+} + Na^{+}\right)} \times 100 \quad (5)$$

### 2.9. Chloralkaline Index (CAI)

*CAI I* and *CAI II* were computed using the Scholler given formula [42], as shown in Equations (6) and (7).

$$CAI\ I = CI^{-} - \frac{\left(Na^{+} + K^{+}\right)}{CI^{-}} \quad (6)$$

$$CAI\ II = CI^{-} - \frac{\left(Na^{+} + K^{+}\right)}{\left[SO_4^{2-} + HCO_3^{-} + NO_3^{-} + CO_3^{2-}\right]} \quad (7)$$

### 2.10. Spital Distribution

GIS is commonly employed in hazard evaluations, spatial mapping, and water quality assessments [43,44]. In this study, ArcGIS (version 10.8) was used to create spatial distribution maps for major cations, anions, and groundwater quality indices.

## 3. Results

### 3.1. pH

pH represents the concentration of hydrogen ions ($H^+$) and hydroxyl ions in water. The research area's groundwater samples had pH values ranging from 7.1 to 7.9.

### 3.2. Electrical Conductivity (EC) and Total Dissolved Solids (TDS)

*EC* is a metric used to quantify salinity and dissolved ions in water samples. The groundwater samples from these 44 UC's showed an average *EC* value of 1354 µS/cm, with values ranging from 401 to 5489 µS/cm. The average TDS in the samples was 886 mg/L, ranging from 256 to 3512 mg/L, as shown in Table 1.

**Table 1.** USDA classification on salinity gradient based on EC and TDS range.

| Category | EC (µs/cm$^{-1}$) | TDS (mg/L) | Hazards and Limitations | Suitable Samples | Suitable Sample (%) |
|---|---|---|---|---|---|
| C1 | <250 | <150 | Low hazards and no detrimental effects on the plants; no accumulation in soil is expected | 0 | 0 |
| C2 | 250–750 | 150–500 | Stress can be shown by sensitive plants, and salt accumulation in soil can be prevented due to moderate leaching | 10 | 22.72 |
| C3 | 750–2250 | 500–1500 | Most plants affected by salinity (salt-tolerant plants are needed); careful irrigation, good drainage, and leaching are needed | 29 | 65.90 |
| C4 | >2250 | >1500 | Unsuitable for irrigation, highly excepting salt-resistant plants; excellent drainage, frequent leaching, and intensive management are needed | 5 | 11.36 |

These results were already reported by [45–48]. EC: Electrical Conductivity; TDS: Todal Dissolved Solids.

### 3.3. Groundwater Quality Based on Major Cation and Anions

In the current study area, the concentration of cations spans from 64.2 to 475.2 mg/L for $Ca^{2+}$, 22.4 to 121.1 mg/L for $Mg^{2+}$, 48.5 to 616.6 mg/L for $Na^+$, and 2.0 to 6.1 mg/L for $K^+$. The measured concentrations of $HCO_3^-$ and $Cl^-$ in groundwater samples vary from 72.0 to 440.9 mg/L, and 200.6 to 592 mg/L, respectively, as shown in Figure 2 and Table 2.

### 3.4. Total Hardness (TH)

According to the Total Hardness (TH) analysis, water samples can be systematically classified into four categories, from soft to extremely hard. The analysis of Total Hardness (TH) indicates that all samples fall within the category of extremely hard quality water, as presented in Table 2.

### 3.5. Sodium Hazard (SH)

#### 3.5.1. Sodium Absorption Ratio (*SAR*)

*SAR* stands out as a critical factor in determining the adequacy of irrigation water quality. The calculated Sodium Adsorption Ratio (*SAR*) within the specified areas varies from 0.09 to 0.83 meq/L.

#### 3.5.2. Soluble Sodium Percentage (SSP)

Irrigation water containing sodium ions initiates an exchange with clay particle $Mg^{2+}$ and $Ca^{2+}$ ions. The Soluble Sodium Percentage in the current study ranged from 2.49 to 27.29%, indicating that all groundwater samples had excellent to good quality, suitable for irrigation.

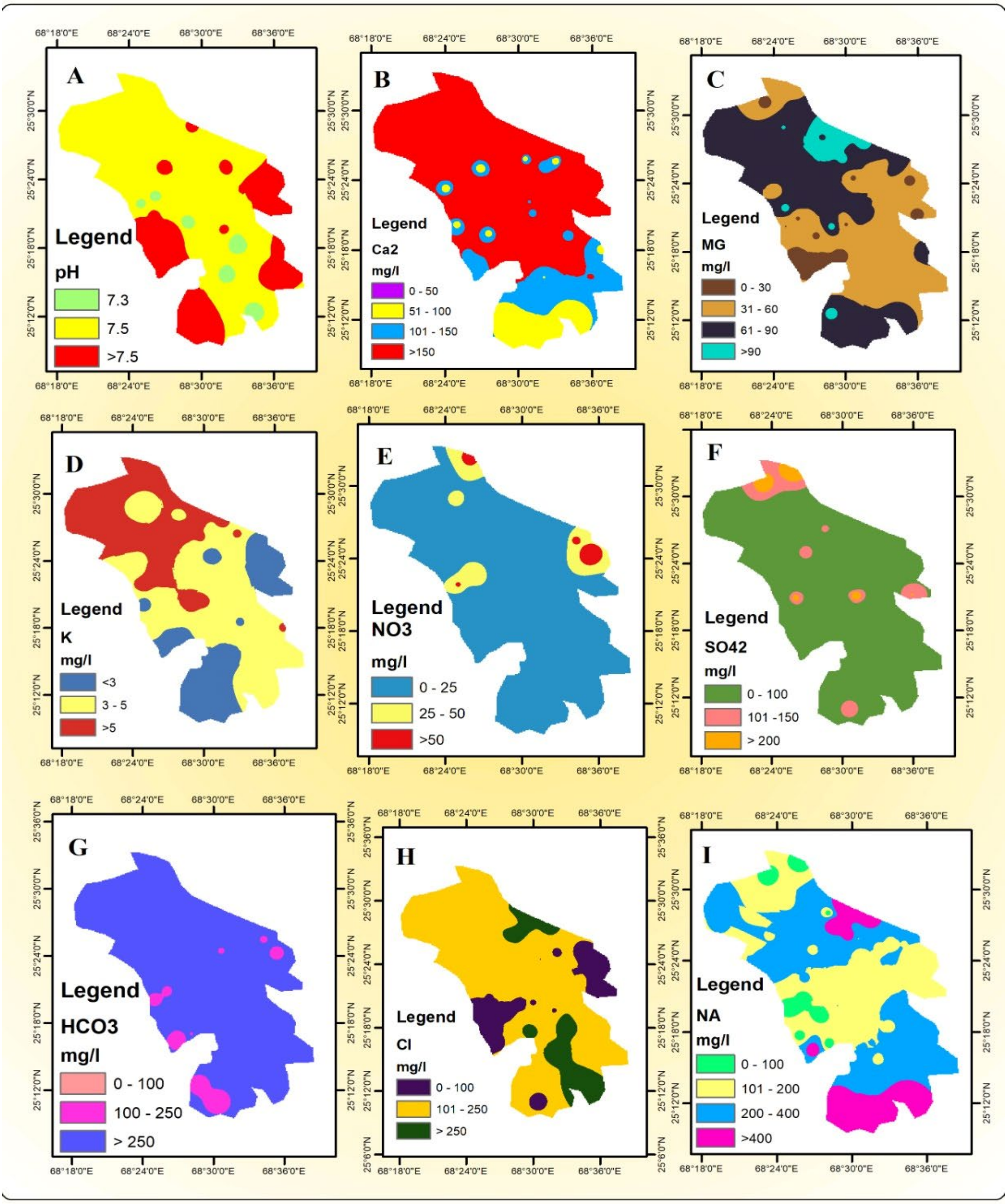



**Figure 2.** Spital distribution of major cations and anions, along with pH.

**Table 2.** Chemical parameters of collected groundwater samples from Rural Hyderabad.

| Sample ID | pH | EC | TH | $Cl^-$ | $HCO_3^-$ | $SO_4^{2-}$ | $NO_3^-$ | $CO_3^{2-}$ | $Ca^{2+}$ | $Mg^{2+}$ | $Na^+$ | $K^+$ | TDS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RH1 | 7.6 | 2051 | 455 | 120.9 | 450.1 | 1.9 | 0.2 | 0 | 64.2 | 73.4 | 197 | 3.4 | 1312.64 |
| RH2 | 7.6 | 1031 | 742 | 191.3 | 499.2 | 11.2 | 1.2 | 0 | 191.3 | 64.9 | 206.2 | 5.1 | 659.84 |
| RH3 | 7.5 | 972 | 316 | 112 | 388.6 | 17.2 | 0.5 | 0 | 47.5 | 47.3 | 177 | 4.2 | 622.08 |
| RH4 | 7.7 | 1371 | 512 | 74.7 | 402.9 | 11.9 | 12.6 | 0 | 120.1 | 51.9 | 181.3 | 3.6 | 877.44 |
| RH5 | 7.7 | 1106 | 1498 | 401.6 | 580.0 | 3.6 | 2.4 | 0 | 400.9 | 121.1 | 621.4 | 6.0 | 707.84 |
| RH6 | 7.5 | 970 | 889 | 392.3 | 577.1 | 121.4 | 10.2 | 0 | 177.4 | 109.4 | 592.3 | 6.1 | 620.8 |
| RH7 | 7.6 | 5489 | 1882 | 224.0 | 592.6 | 17.4 | 0.1 | 0 | 391.2 | 97.4 | 488.2 | 5.1 | 3512.96 |
| RH8 | 7.6 | 693 | 1603 | 381.4 | 388.7 | 19.3 | 4.8 | 0 | 475.2 | 101.3 | 616.6 | 5.0 | 443.52 |
| RH9 | 7.6 | 2031 | 788 | 180.1 | 430.6 | 4.7 | 6.8 | 0 | 180.9 | 80.9 | 185.4 | 4.1 | 1299.84 |
| RH10 | 7.6 | 1477 | 641 | 110.0 | 466.4 | 21.9 | 4.6 | 0 | 147.6 | 67.3 | 166.9 | 4.7 | 945.28 |
| RH11 | 7.5 | 1191 | 667 | 219.3 | 402.9 | 211.4 | 12.6 | 0 | 122.9 | 87.2 | 150.8 | 4.5 | 762.24 |
| RH12 | 7.7 | 2755 | 530 | 197.4 | 400.8 | 121.12 | 16.2 | 0 | 72.6 | 84.2 | 187.5 | 5.0 | 1763.2 |
| RH13 | 7.3 | 2201 | 1399 | 160.3 | 470.1 | 17.3 | 49.4 | 0 | 440.9 | 73.2 | 216.3 | 5.5 | 1408.64 |
| RH14 | 7.3 | 2314 | 1361 | 215.6 | 485.2 | 7.8 | 53.1 | 0 | 381.3 | 100.2 | 179.4 | 5.5 | 1480.96 |
| RH15 | 7.2 | 2198 | 1159 | 77.3 | 433.5 | 2.9 | 0.1 | 0 | 299.6 | 99.1 | 200.7 | 5.5 | 1406.72 |
| RH16 | 7.4 | 2007 | 1285 | 91.4 | 467.7 | 1.3 | 0.9 | 0 | 471.5 | 27.5 | 195.6 | 4.9 | 1284.48 |
| RH17 | 7.1 | 1674 | 813 | 440.9 | 530.4 | 1.4 | 9.1 | 0 | 256.9 | 41.2 | 171.3 | 3.1 | 1071.36 |
| RH18 | 7.5 | 2179 | 535 | 327.1 | 522.4 | 27.6 | 1.4 | 0 | 176.3 | 22.9 | 199.2 | 3.6 | 1394.56 |
| RH19 | 7.3 | 677 | 476 | 299.1 | 567.2 | 77.2 | 9.4 | 0 | 99.4 | 55.2 | 187.2 | 2.9 | 433.28 |
| RH20 | 7.3 | 547 | 428 | 422.0 | 591.1 | 91.3 | 3.1 | 0 | 64.2 | 64.9 | 554.2 | 4.1 | 350.08 |
| RH21 | 7.7 | 765 | 475 | 72.0 | 200.6 | 117.2 | 0.2 | 0 | 74.1 | 71.2 | 502.3 | 2.0 | 489.6 |
| RH22 | 7.9 | 1109 | 591 | 117.8 | 221.3 | 7.8 | 0.4 | 0 | 81.4 | 95.3 | 449.6 | 2.6 | 709.76 |
| RH23 | 7.8 | 556 | 1346 | 91.0 | 202.9 | 3.1 | 0.2 | 0 | 100.3 | 22.4 | 552.1 | 2.1 | 355.84 |
| RH24 | 7.8 | 811 | 602 | 100.3 | 247.3 | 9.2 | 0.1 | 0 | 204.9 | 22.5 | 48.5 | 2.1 | 519.04 |
| RH25 | 7.5 | 517 | 574 | 164.9 | 433.2 | 177.3 | 3.5 | 0 | 191.3 | 22.7 | 61.5 | 5.1 | 330.88 |
| RH26 | 7.5 | 1351 | 1144 | 121.1 | 399.2 | 191.5 | 57.5 | 0 | 372.2 | 52.3 | 47.7 | 5.6 | 864.64 |
| RH27 | 7.4 | 977 | 1516 | 144.7 | 371.2 | 11.7 | 11.3 | 0 | 461.5 | 87.2 | 50.1 | 4.1 | 625.28 |
| RH28 | 7.6 | 559 | 1121 | 126.7 | 444.2 | 33.7 | 29 | 0 | 299.4 | 90.4 | 188.4 | 3.9 | 357.76 |
| RH29 | 7.6 | 1171 | 940 | 204.0 | 410.1 | 49.2 | 4.2 | 0 | 268.4 | 65.3 | 222.5 | 5.5 | 749.44 |
| RH30 | 7.5 | 2515 | 956 | 211.3 | 422.4 | 1.8 | 3.5 | 0 | 264.7 | 71.4 | 204.1 | 5.1 | 1609.6 |
| RH31 | 7.4 | 401 | 1391 | 197.2 | 471.8 | 16.3 | 1.1 | 0 | 411.2 | 87.2 | 198.2 | 5.1 | 256.64 |
| RH32 | 7.5 | 1904 | 392 | 126.2 | 489.4 | 62.2 | 0.9 | 0 | 72.6 | 51.3 | 300.1 | 4.1 | 1218.56 |
| RH33 | 7.7 | 1373 | 541 | 100.4 | 380.2 | 98.2 | 1.3 | 0 | 91.4 | 76.3 | 299.6 | 4.8 | 878.72 |
| RH34 | 7.8 | 1426 | 572 | 133.9 | 399.6 | 8.1 | 0.2 | 0 | 150.3 | 49.2 | 326.4 | 4.6 | 912.64 |
| RH35 | 7.6 | 2141 | 490 | 109.1 | 303.4 | 5.7 | 0.1 | 0 | 122.7 | 45.4 | 351.2 | 4.0 | 1370.24 |
| RH36 | 7.7 | 1632 | 927 | 89.6 | 305.5 | 1.2 | 11.4 | 0 | 301.4 | 42.4 | 199.9 | 4.0 | 1044.48 |
| RH37 | 7.5 | 422 | 1282 | 56.0 | 222.6 | 9.4 | 57.2 | 0 | 377.3 | 81.4 | 199.2 | 1.9 | 270.08 |
| RH38 | 7.9 | 637 | 760 | 71.3 | 221.9 | 9.3 | 72.9 | 0 | 266.4 | 22.9 | 171.4 | 2.3 | 407.68 |
| RH39 | 7.6 | 502 | 598 | 99.3 | 216.3 | 29.4 | 9.1 | 0 | 198.4 | 24.6 | 123.4 | 2.1 | 321.28 |
| RH40 | 7.8 | 876 | 612 | 47.4 | 255.7 | 151.2 | 0.6 | 0 | 205.5 | 25.3 | 151.2 | 2.1 | 558.08 |
| RH41 | 7.7 | 811 | 646 | 92.6 | 200.4 | 177.2 | 0.2 | 0 | 211.8 | 27.8 | 51.2 | 4.2 | 519.04 |
| RH42 | 7.7 | 803 | 317 | 49.3 | 199.4 | 3.1 | 7.2 | 0 | 76.4 | 29.7 | 47.4 | 2.6 | 513.92 |
| RH43 | 7.9 | 783 | 459 | 47.8 | 264.2 | 9.4 | 8.1 | 0 | 144.2 | 23.9 | 67.2 | 3.6 | 501.12 |
| RH44 | 7.9 | 614 | 1301 | 64.9 | 292.6 | 12.9 | 0.2 | 0 | 77.9 | 26.4 | 40.3 | 4.5 | 392.96 |
| Range | 7.1–7.9 | 401–5489 | 318–1882 | 47.4–440.9 | 199.4–592.6 | 1.2–211.4 | 0.1–72.9 | 0–0 | 47.5–475.2 | 22.4–121.1 | 40.3–621.4 | 1.9–6.1 | 256.6–3512.7 |
| Mean | 7.5 | 1354 | 853.0 | 165.4 | 391.4 | 45.13 | 10.89 | 0 | 218.3 | 61.0 | 239.2 | 4.0 | 866.71 |

Detailed insights of chemical parameters from 44 samples of the study areas.

*3.6. Residual Soluble Percentage (RSP) or Residual Sodium Carbonate (RSC)*

The *RSC* values seen in the collected water samples ranged from −24.26 to 1.07 meq/L. It is noteworthy that, based on the assessment of Residual Sodium Carbonate (*RSC*) values, all samples were found to be fit for agricultural purposes, as detailed in Figure 3 and Table 3.

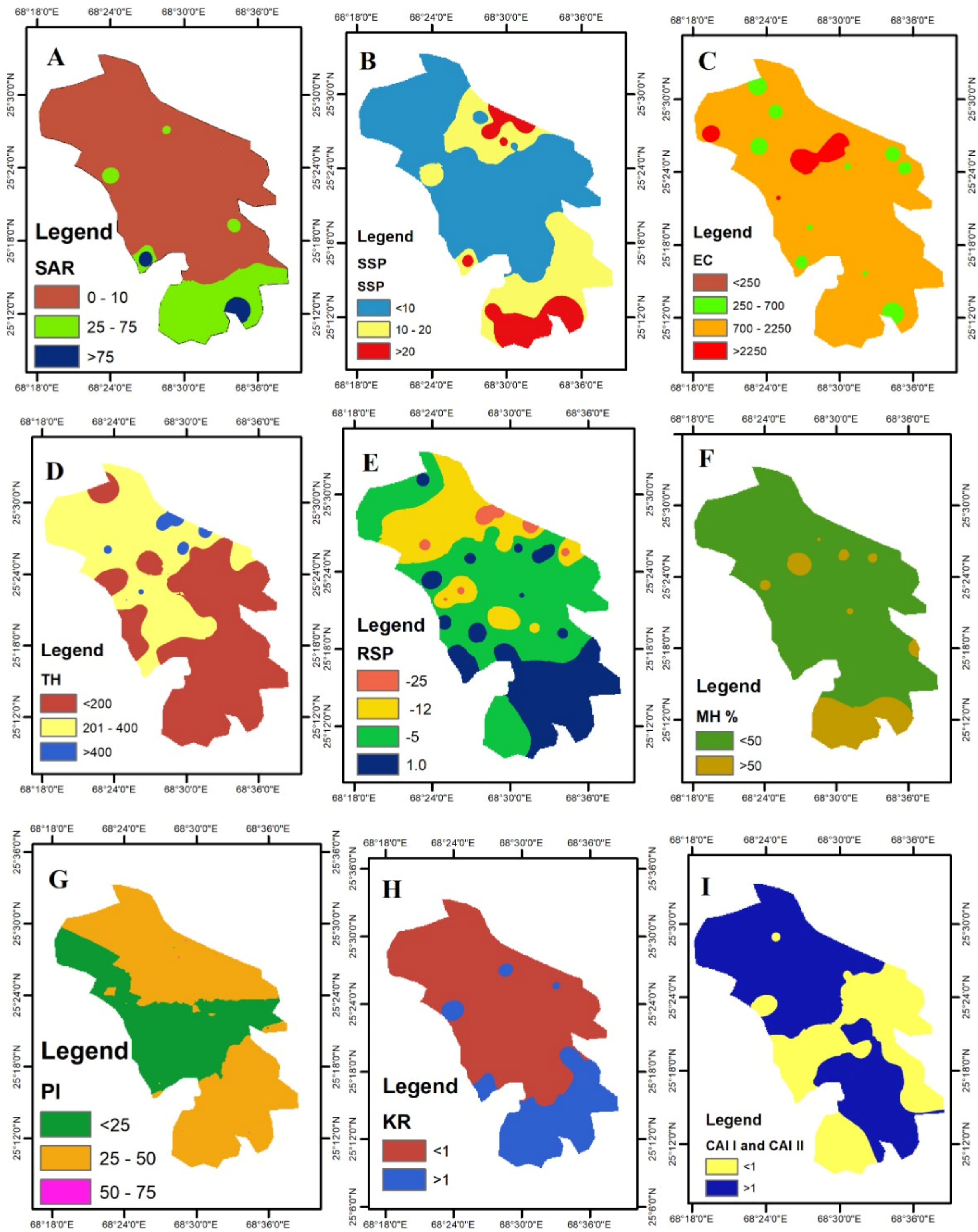



**Figure 3.** Spital distribution map for irrigation water quality.

**Table 3.** Area-wise irrigation suitability indices.

| Sample ID | *SAR* | *SSP* | *RSC* | *MH* | *PI* | KR | *CAI I* | *CAI II* | Gibbs I | Gibbs II |
|---|---|---|---|---|---|---|---|---|---|---|
| RH1 | 0.46 | 9.05 | −1.95 | 66 | 8.72 | 0.92 | 0.88 | 2.25 | 0.32 | 0.73 |
| RH2 | 0.30 | 9.51 | −6.79 | 36 | 9.08 | 0.60 | 3.72 | 4.33 | 0.40 | 0.49 |
| RH3 | 0.61 | 8.46 | 0.05 | 62 | 7.88 | 1.22 | 0.70 | 2.01 | 0.33 | 0.77 |
| RH4 | 0.38 | 8.39 | −3.73 | 42 | 8.02 | 0.76 | −1.67 | 0.98 | 0.26 | 0.57 |
| RH5 | 0.45 | 27.29 | −20.63 | 33 | 27.07 | 0.90 | 8.95 | 8.52 | 0.54 | 0.58 |
| RH6 | 0.72 | 26.11 | −8.53 | 51 | 25.82 | 1.43 | 8.74 | 8.95 | 0.54 | 0.74 |
| RH7 | 0.38 | 21.49 | −17.96 | 29 | 21.29 | 0.77 | 2.95 | 4.21 | 0.39 | 0.52 |
| RH8 | 0.42 | 27.03 | −25.83 | 26 | 26.85 | 0.83 | 8.27 | 6.84 | 0.63 | 0.53 |
| RH9 | 0.26 | 8.50 | −8.73 | 43 | 8.17 | 0.51 | 3.48 | 3.96 | 0.42 | 0.47 |
| RH10 | 0.28 | 7.85 | −5.34 | 43 | 7.39 | 0.56 | 0.73 | 2.21 | 0.29 | 0.50 |
| RH11 | 0.24 | 7.13 | −6.81 | 54 | 6.69 | 0.49 | 5.12 | 5.60 | 0.49 | 0.52 |
| RH12 | 0.38 | 8.83 | −4.08 | 66 | 8.29 | 0.77 | 4.09 | 4.69 | 0.47 | 0.70 |
| RH13 | 0.17 | 9.78 | −20.44 | 22 | 9.48 | 0.33 | 2.42 | 3.45 | 0.41 | 0.30 |
| RH14 | 0.14 | 8.20 | −19.46 | 30 | 7.88 | 0.28 | 4.79 | 5.21 | 0.47 | 0.29 |
| RH15 | 0.19 | 9.17 | −16.13 | 36 | 8.81 | 0.38 | −1.88 | 0.95 | 0.24 | 0.37 |
| RH16 | 0.16 | 8.87 | −18.20 | 9 | 8.58 | 0.33 | −0.76 | 1.46 | 0.25 | 0.27 |
| RH17 | 0.23 | 7.78 | −7.58 | 21 | 7.57 | 0.46 | 11.85 | 11.61 | 0.59 | 0.37 |
| RH18 | 0.40 | 9.13 | −2.16 | 18 | 8.81 | 0.81 | 8.29 | 8.28 | 0.52 | 0.50 |
| RH19 | 0.43 | 8.56 | −0.27 | 48 | 8.31 | 0.85 | 7.48 | 7.71 | 0.48 | 0.62 |
| RH20 | 1.40 | 24.42 | 1.07 | 63 | 24.19 | 2.80 | 9.89 | 9.84 | 0.55 | 0.88 |
| RH21 | 1.13 | 22.00 | −6.35 | 62 | 21.90 | 2.27 | −8.73 | −1.78 | 0.38 | 0.86 |
| RH22 | 0.81 | 19.76 | −8.38 | 66 | 19.61 | 1.63 | −2.57 | −1.84 | 0.48 | 0.83 |
| RH23 | 1.74 | 24.18 | −3.56 | 27 | 24.06 | 3.49 | −6.79 | −4.52 | 0.44 | 0.83 |
| RH24 | 0.09 | 2.49 | −8.07 | 15 | 2.25 | 0.17 | 2.07 | 2.32 | 0.41 | 0.17 |
| RH25 | 0.12 | 3.59 | −4.36 | 17 | 2.86 | 0.23 | 4.06 | 4.40 | 0.40 | 0.23 |
| RH26 | 0.05 | 2.64 | −16.42 | 19 | 2.18 | 0.09 | 2.77 | 3.23 | 0.40 | 0.11 |
| RH27 | 0.04 | 2.50 | −24.26 | 24 | 2.25 | 0.07 | 3.53 | 3.74 | 0.41 | 0.09 |
| RH28 | 0.18 | 8.52 | −15.22 | 33 | 8.28 | 0.36 | 1.26 | 2.60 | 0.36 | 0.36 |
| RH29 | 0.26 | 10.17 | −12.14 | 29 | 9.76 | 0.51 | 4.06 | 4.51 | 0.46 | 0.42 |
| RH30 | 0.23 | 9.34 | −12.26 | 31 | 8.97 | 0.46 | 4.46 | 4.69 | 0.47 | 0.40 |
| RH31 | 0.15 | 8.97 | −20.09 | 26 | 8.69 | 0.31 | 4.00 | 4.49 | 0.42 | 0.30 |
| RH32 | 0.83 | 13.55 | 0.12 | 54 | 13.18 | 1.65 | −0.12 | 2.16 | 0.31 | 0.78 |
| RH33 | 0.60 | 13.54 | −4.70 | 58 | 13.13 | 1.19 | −1.80 | 1.25 | 0.31 | 0.74 |
| RH34 | 0.61 | 14.65 | −5.06 | 35 | 14.29 | 1.22 | 0.00 | 1.65 | 0.37 | 0.66 |
| RH35 | 0.77 | 15.68 | −4.94 | 38 | 15.36 | 1.54 | −1.91 | 0.06 | 0.38 | 0.71 |
| RH36 | 0.23 | 9.07 | −13.60 | 19 | 8.77 | 0.47 | −0.94 | 0.85 | 0.35 | 0.37 |
| RH37 | 0.17 | 8.80 | −22.00 | 26 | 8.72 | 0.34 | −3.92 | −0.24 | 0.41 | 0.32 |
| RH38 | 0.24 | 7.71 | −11.59 | 13 | 7.54 | 0.49 | −1.72 | 0.51 | 0.47 | 0.36 |
| RH39 | 0.22 | 5.67 | −8.42 | 17 | 5.47 | 0.45 | 0.87 | 1.55 | 0.45 | 0.35 |
| RH40 | 0.27 | 6.86 | −8.19 | 17 | 6.68 | 0.53 | −3.61 | 0.44 | 0.24 | 0.39 |
| RH41 | 0.09 | 2.93 | −9.62 | 18 | 2.35 | 0.17 | 1.72 | 2.28 | 0.44 | 0.18 |
| RH42 | 0.16 | 2.85 | −3.03 | 39 | 2.28 | 0.33 | −0.14 | 0.78 | 0.32 | 0.36 |
| RH43 | 0.16 | 3.68 | −4.87 | 22 | 3.09 | 0.32 | −0.88 | 0.70 | 0.25 | 0.29 |
| RH44 | 0.14 | 3.20 | −1.30 | 36 | 2.03 | 0.29 | 0.81 | 1.46 | 0.28 | 0.32 |
| Range | 0.04–1.74 | 2.49–27.29 | −25.83–1.07 | 9–66 | 2.03–27.07 | 0.07–3.49 | −8.73–11.85 | −4.52–11.61 | 0.24–0.63 | 0.09–0.88 |
| Mean | 0.39 | 10.86 | 6.04 | 34.98 | 10.51 | 0.79 | 1.92 | 3.14 | 0.40 | 0.48 |

This table is providing the detailed insights for the area-wise irrigation suitability insights of the study areas.

### 3.7. Magnesium Hazard (MH)

Water samples with MH values of more than 50 are considered unsuitable for irrigation. As shown in Figure 4, 22% of the samples in the current investigation exceeded the value of permitted limits, with MH values ranging from 9 to 66% of samples, although 78% of the samples seem suitable for irrigation.

### 3.8. Permeability Index (PI)

It is advised to use water that falls into Classes I and II for irrigation. The Permeability Index (*PI*) for 44 samples in the chosen study area ranges from 2.18 to 27.07 meq/L, as shown in Figure 4. In conclusion, the evaluation finds that the land is deemed appropriate for irrigation.

### 3.9. Kelley's Ratio (KR)

The groundwater's Kelley's ratio values in Rural Hyderabad ranged from 0.09 to 1.63. Based on this indicator, just 15% of the water samples were deemed unsuitable for irrigation, with the remaining 85% being found to be appropriate.

### 3.10. USSL Salinity Diagram

Based on plotted data shown in Figure 5, 25.0%, 68.18%, and 6.82% of samples come under the C2S1, C3S1, and C4S1 categories. Salinity ranges in the overall research area range from low to high, as illustrated in Figure 4.

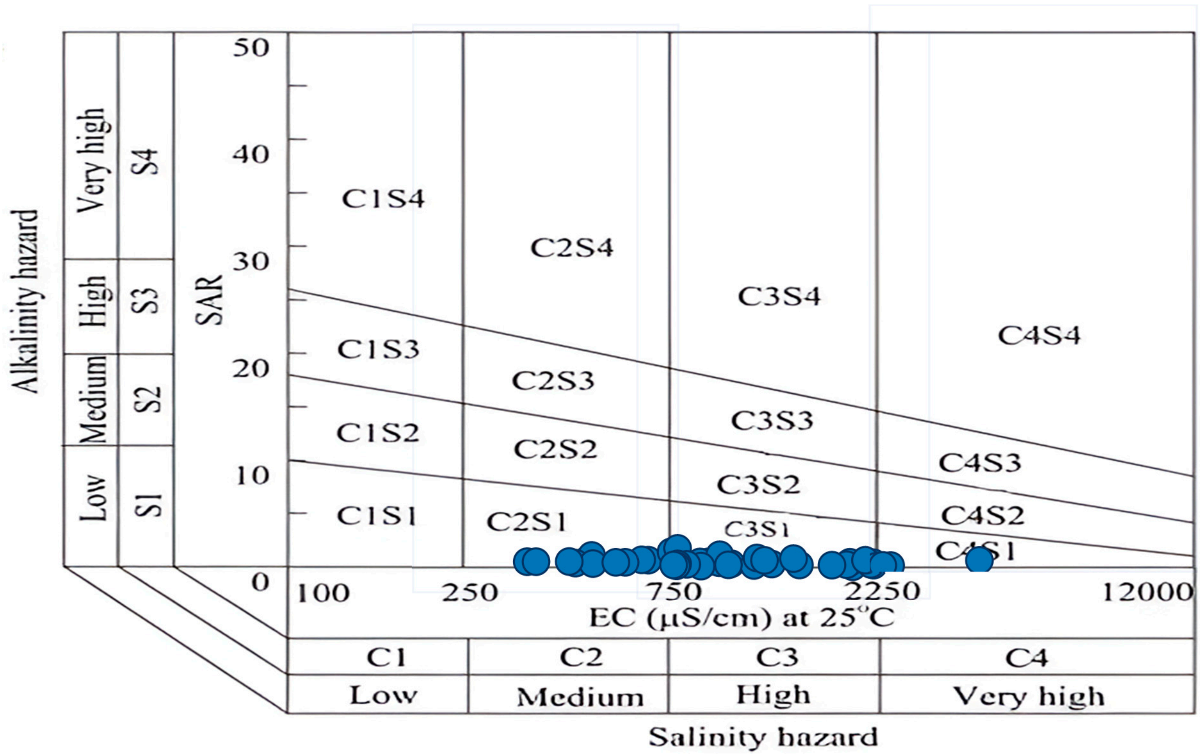



**Figure 4.** USSL diagram showing groundwater suitability for irrigation.

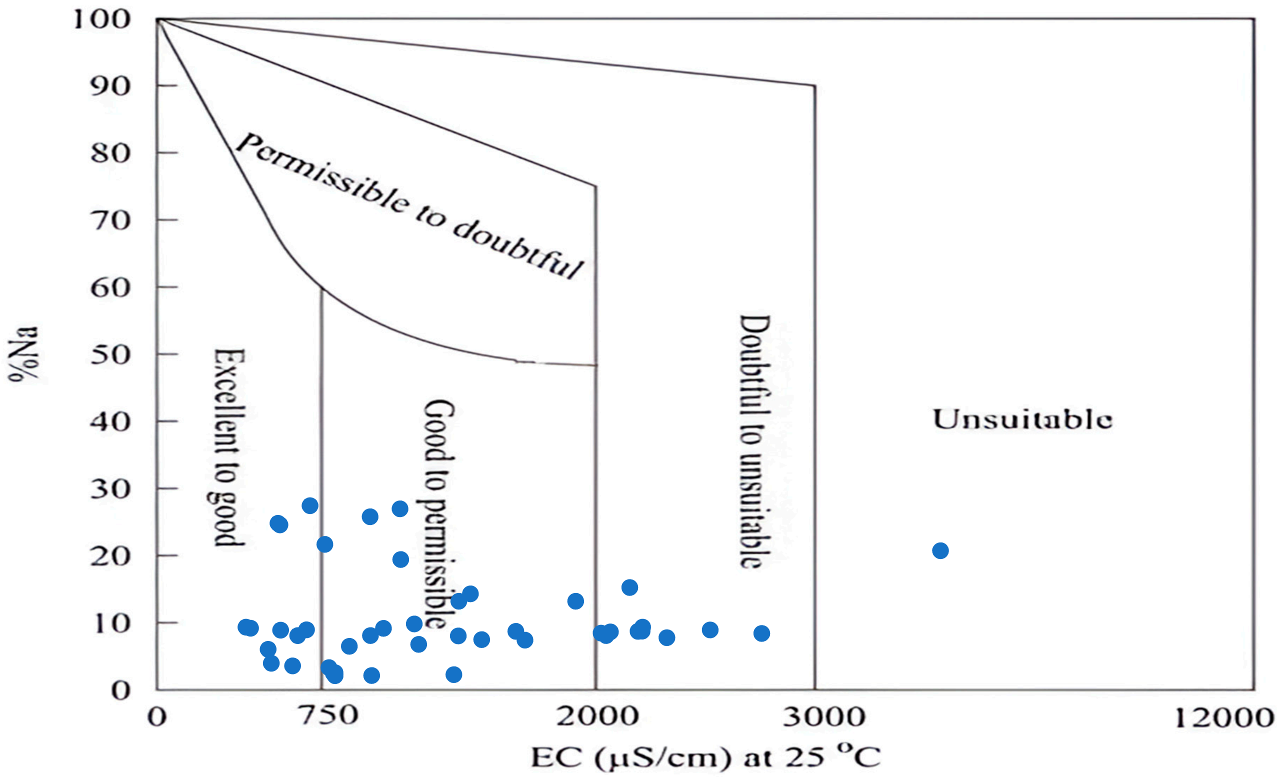



**Figure 5.** Wilcox diagram showing suitability of groundwater.

### *3.11. Wilcox Diagram*

The Wilcox diagram is employed to assess the suitability of groundwater quality for irrigation purposes. This classification system delineates the following four distinct classes:

excellent to good (C1), good to permissible (C2), doubtful to unsuitable (C3), and unsuitable (C4). In the study area, 25% and 43% of the samples fall within the (C1) and (C2) categories, with 30% classified under (C3), and 2% under (C4) in the Wilcox diagram assessment, as shown in Figure 5.

### *3.12. Hydrochemistry of Groundwater*

#### 3.12.1. Chloralkaline Index (*CAI I* and *II*)

The *CAI I* values obtained ranged from −8.73 to 9.89, while *CAI II* values varied between −4.52 and 11.61, as shown in Table 3. Most samples showed a positive ratio, demonstrating the dominance of positive ion exchange.

#### 3.12.2. Gibbs Ratio (GR)

The Gibbs diagram illustrates the following three distinct fields: precipitation dominance, evaporation dominance, and rock dominance. In our analysis, the Gibbs ratio was calculated by considering the concentration of all ions in milliequivalents per liter (meq/L). This diagram was then constructed by plotting the Gibbs ratio (either cation or anion) against the Total Dissolved Solids.

In the study area under investigation, Gibbs ratio 1 exhibited a range spanning from 0.24 to 0.63, with an average value of 0.40. Similarly, Gibbs ratio 2 showcased variations ranging from 0.09 to 0.88, with an average value of 0.48, as depicted in Figure 6.

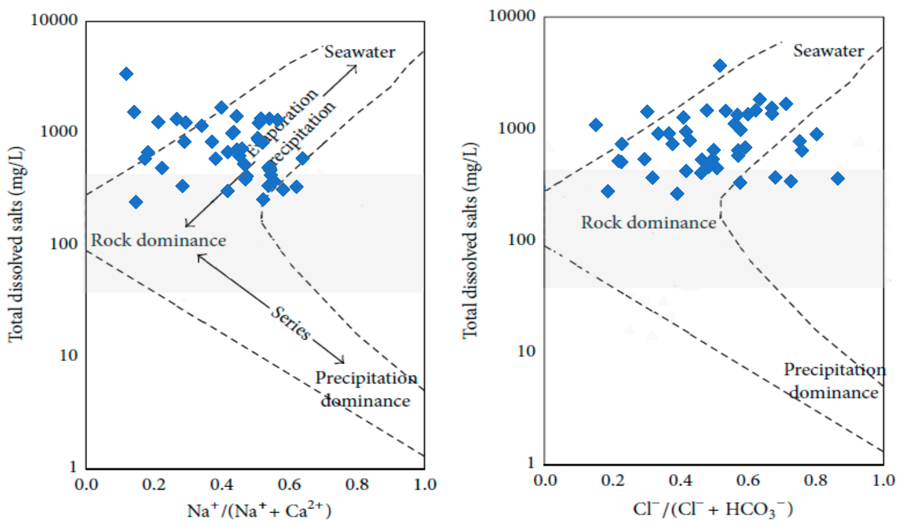
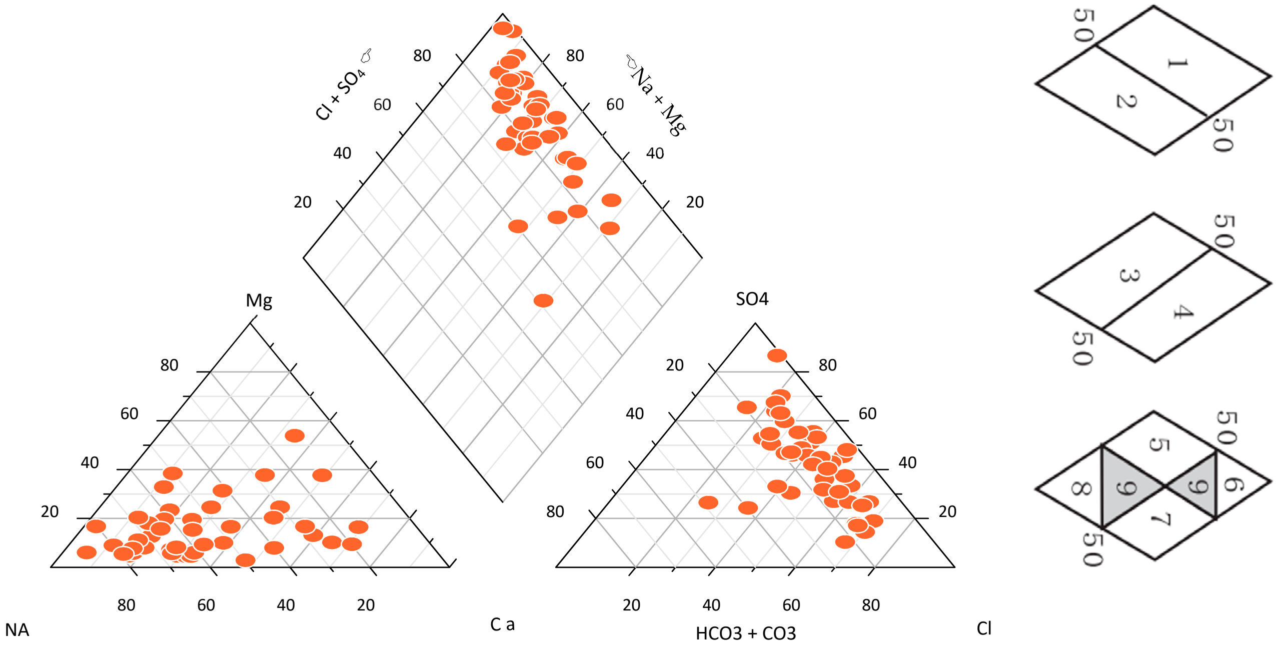



**Figure 6.** Gibbs diagram correlating cations and anions in relation to Total Dissolved Solids (TDS).

#### 3.12.3. Piper and Durov Diagrams

The hydrochemical analysis of the examined samples involved a comprehensive interpretation by plotting the data onto the Piper diagram, Figure 7a,b, and the Durov diagrams, shown in Figures 7 and 8. Based on these graphs, the Piper diagram showed that cations in the water sample were mainly $Na^+$ and $Mg^{2+}$, with content ranging from 20% to 100%. The anions were mainly $SO_4{}^{2-}$ and $Cl^-$, with content ranging from 50% to 100%. The main type of water quality was magnesium sodium sulphate type water. Although a small amount of magnesium sulphate can be used as a fertilizer in agriculture, excessive application of magnesium sulfate can cause harm to plant growth and quality. The Durov diagram revealed that cations were dominated by $Na^+$, followed by $Ca^{2+}$ and $Mg^{2+}$, while anions were dominated by $HCO^{3-}$, followed by $Cl^-$ and $SO_4{}^{2-}$.




(**a**) (**b**)

**Figure 7.** (**a**) Classification of water sample according to piper diagram. (**b**) Piper diagram diamond-shaped field partition.

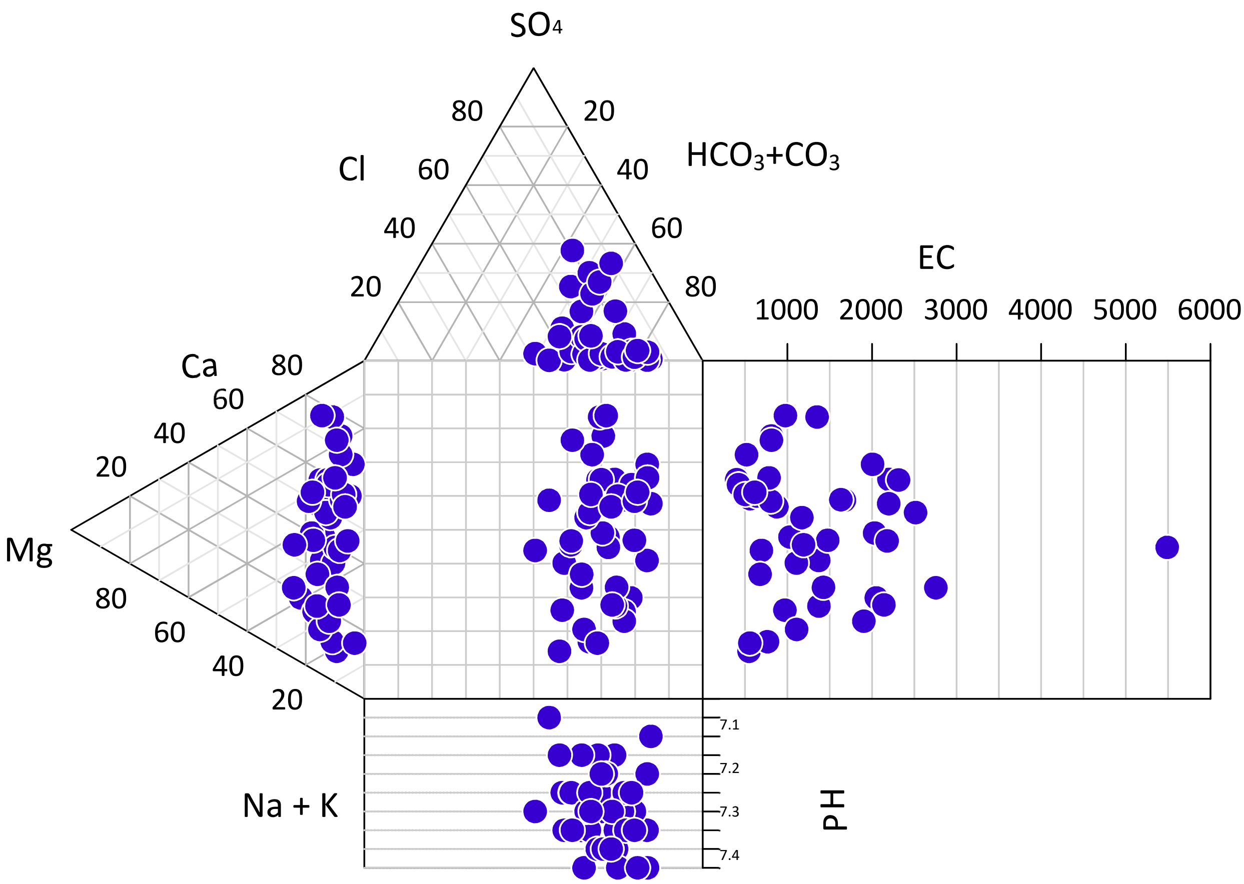



**Figure 8.** Classification of water sample according to the Durov diagram.

## 4. Discussion

### *4.1. pH*

The impact of extreme pH values on crop development and productivity has been highlighted by Arshad and Shakoor (2017) [49], with significant implications for nutrient availability [50,51]. However, in this investigation, pH values exhibited minimal variation, all of which were deemed safe for irrigation [52].

### *4.2. EC and TDS*

Processes such as aquifer material dissolving or leaching, mixing saline sources, or a combination of these can contribute to elevated Electrical Conductivity (EC) levels in water [53]. Irrigation water can be categorized into the following four different classes based on its EC and Total Dissolved Solids (TDS): C1, C2, C3, and C4. As reported in Table 1, the distribution of these categories in the samples is as follows: 0% in C1, 25% in C2, 65% in C3, and 10% in C4.

### *4.3. Groundwater Quality Based on Major Cations and Anions*

According to established standards, the permissible limits for $Ca^{2+}$, $Mg^{2+}$, $Na^{+}$, and $K^{+}$ in irrigation water are 80, 35, 200, and 30 mg/L, respectively [3,5,34,36]. Upon examination of groundwater concentrations in relation to these limits, it was observed that 13%, 11%, and 40% of samples exceeded permissible thresholds for $Ca^{2+}$, $Mg^{2+}$, and $Na^{+}$, respectively, while $K^{+}$ levels remained within acceptable limits (Table 2).

Regarding anions, the permissible limits for $HCO^{3-}$ and $Cl^{-}$ are set at 250 mg/L [38,54,55]. Analysis of major anions revealed that 43% of water samples adhered to the $HCO^{3-}$ limit, while only 9% conformed to the $Cl^{-}$ limit, indicating their unsuitability for irrigation purposes. However, for $SO4^{2-}$, $NO^{3-}$, and $CO3^{2-}$, with permissible limits set at 1000, 50, and 50 mg/L [56], it was found that 100% of observed values fell within permissible limits.

### *4.4. TH*

In 2014, Sappa emphasized that measuring water hardness is a practical method for assessing water quality intended for domestic, agricultural, and industrial purposes [57]. Furthermore, Sawyer and McCarthy's classification system divides water hardness into four distinct classes [58], as follows: soft (<75 mg/L), moderately hard (75 to 150 mg/L), hard (150 to 300 mg/L), and very hard (>300 mg/L). However, based on our results, none of the samples fell within the categories of soft, moderately hard, or hard; instead, all water samples were categorized as extremely hard.

### *4.5. SH*

#### 4.5.1. *SAR*

As noted by Elbilali and Taleb (2020), Dlamini et al. (2021), and Pahnwar et al. (2022), elevated Sodium Adsorption Ratio (*SAR*) values indicate that water may not be suitable for irrigation [59–61]. High salt content relative to calcium and magnesium could adversely affect soil permeability, hindering the flow of water necessary for crop development [60,62]. *SAR* evaluations typically categorize water suitability for irrigation into the following three categories: values between 0 and 10 meq/L are considered excellent, values between 10 and 18 meq/L are deemed good, and values over 18 meq/L are determined to be unsuitable. Based on our results, all samples fall under the excellent category.

#### 4.5.2. *SSP*

The study by Soomro et al. (2014) underscores the significance of the Soluble Sodium Percentage as a crucial factor in irrigation classification [63]. This sodium exchange process can reduce soil permeability, leading to inadequate internal drainage, soil compaction, and subsequent negative impacts on soil quality and seedling emergence [64]. Moreover, elevated sodium levels promote interactions with carbonates and chlorides, resulting in salinized and alkaline soils. Based on the five classifications for irrigation water quality ranging from excellent to inappropriate as reported earlier [65], all water quality samples were found to be suitable for irrigation.

### 4.6. RSC

The excess quantity of carbonate and bicarbonate compared to alkaline earth metal ions ($Ca^{2+}$ and $Mg^{2+}$) plays a significant role in deciding the suitability of groundwater for irrigation [16,46,66]. This surplus, known as Residual Sodium Carbonate (*RSC*), becomes crucial in understanding water quality. Elevated *RSC* values suggest a precipitation of a substantial amount of calcium and magnesium ions from the solution, leading to an increase in sodium concentration in both water and soil particles. Based on provided results in Table 3, all samples were fit for irrigation.

### 4.7. MH

After decreasing soil infiltration capacity and negatively affecting crop output, elevated concentrations of any cation can raise soil pH and EC [67]. An assessment of the magnesium danger was carried out in this study due to the greater magnesium concentration seen in the samples that were collected. Crop productivity is negatively impacted by soil alkalinity, which occurs when the Magnesium Hazard (MH) value rises beyond 50% [68]. It is noteworthy that, based on the provided results in Table 3, 78 of the water samples fall under permissible limits.

### 4.8. PI

The entire production process is impacted by the reduced water supply to crops because of the soil's low permeability [69]. This decrease in water availability causes problems including surface soil waterlogging, seedbed crusting, and the start of related concerns like infections, salinity, weed growth, oxygen shortage, and nutritional difficulties [70]. A classification system based on the Permeability Index (*PI*) is used to determine the permeability of the soil. As Doneen (1975) has already discussed, *PI* can be stratified into the following three distinct classes: Class I (>75 percent, indicating suitability), Class II (25–75%, denoting goodness), and Class III (<25 percent, indicating unsuitability) [41,71]. Interestingly, every one of these samples from the study area fits into Class I, indicating that they are suitable for irrigation.

### 4.9. KR

When determining whether groundwater is suitable for irrigation, Kelley's ratio is a useful tool [25,37,72]. An elevated sodium level indicates that the groundwater is inappropriate for irrigation when the Kelley's ratio is more than one [72]. The KR values are divided into two groups, as follows: those with values less than one (1), which indicate that irrigation is appropriate; and those with values greater than one (1), which indicate that irrigation is not appropriate. Based on the results, KR values showed 85% suitability in the studied area.

### 4.10. USSL Salinity Diagram

In 1994, USSL proposed a diagram in which *SAR* is plotted versus EC in this graphic representation [73]. For groundwater quality for irrigation, the USSL diagram is a useful tool [69]. As seen in Figure 5, this graph divides groundwater quality into 16 classes on both the alkaline and salinity spectrums. The USSL graph indicated that most samples fall under the C3S1 category, which is known as high salinity and low sodium water.

### 4.11. Wilcox Diagram

In 1948, Wilcox introduced a diagram to assess the groundwater suitability for irrigation [74]. The same research conducted earlier concludes that this diagram illustrates the relationship between the elective salinity and sodium percentages [75]. Overall, the groundwater in the study area is found to be suitable for irrigation, except for specific cases, highly involving salt-resistant plants. Successful use would need excellent drainage, regular leaching, and intensive management practices.

### *4.12. Hydrochemistry of Groundwater*

#### 4.12.1. Chloralkaline Index (*CAI I* and *II*)

Cation exchange between $Na^+$ and $Ca^{2+}$ is an important natural process with significant influences on groundwater chemistry [76]. There are two chloralkaline indices (*CAI I* and *CAI II*), as introduced by researcher [42]. A positive Chloralkaline Index value signifies a direct ion exchange involving $Na^+$ and $K^+$ from water, and $Ca^{2+}$ and $Mg^{2+}$ from rocks. Conversely, a negative CAI shows an ion exchange between $Mg^{2+}$ and $Ca^{2+}$ from water, and $Na^+$ and $K^+$ from rocks. In direct exchange, positive indices signify the ion exchange involving $Na^+$ and $K^+$ from water, occurring with $Mg^{2+}$ and $Ca^{2+}$ present in the rock. Conversely, in indirect exchange, the ion exchange takes place in the opposite sequence, and the indices are determined to be negative. Based on the results, most groundwater samples showed positive ion exchange between each other.

#### 4.12.2. GR

In 1977, Gibbs introduced a diagram aimed at interpreting the major ion chemistry mechanisms within groundwater samples [77]. Current observations vividly portray the distribution of samples, depicting a significant concentration within the evaporation dominance area. This observation underscores a substantial impact of both precipitation and evaporation processes on the sampled water compositions. The prevalence of samples within the evaporation domain emphasizes the noteworthy influence of climatic factors, reflecting a discernible concentration of ions due to evaporation effects in the study area.

#### 4.12.3. Piper and Durov Diagram

Within the Piper diagram, the chemical data were systematically positioned in two triangular fields, converging into an upper diamond-shaped field [78]. This partition of the Piper diagram is illustrated in Figure 7a,b. Water samples falling into different zones of the diamond-shaped field exhibit distinct chemical characteristics. The diamond-shaped field provides an overview of the general chemical characteristics of water samples, while the triangular fields reveal the relative content of various ions. In this study, groundwater samples predominantly fell within zones six and nine of the diamond-shaped field, with few samples in zone seven. The ions in these samples consisted mainly of alkaline earth metal ions and strong acid ions, with non-carbonate hardness exceeding 50%. For plants susceptible to salinity, such as those in the study area, careful irrigation, excellent drainage, and regular leaching are necessary when utilizing groundwater irrigation. The Durov diagram, presented in Figure 8, illustrates the dominance of certain cations and anions over each other, providing further insights into the chemical composition of the water samples.

## 5. Conclusions

The analysis of groundwater quality in rural areas of Hyderabad for irrigation purposes reveals the following conclusions.

Groundwater in these regions is characterized by high salinity and low sodium content, which may pose risks to plants with low salt tolerance. However, it remains suitable for irrigation of highly salt-tolerant plants, contingent upon robust management practices including effective drainage, regular leaching, and intensive management.

A total of 44 groundwater samples collected from 11 Union Councils demonstrate pH levels within acceptable ranges. Nevertheless, approximately 26% of samples exceeded acceptable Electrical Conductivity (EC) levels, indicating potential concerns for irrigation suitability. Moreover, elevated concentrations of $Ca^{2+}$, $Mg^{2+}$, and $Na^+$ ions were observed in a significant proportion of samples, categorizing the groundwater as extremely hard water.

Key hydrochemical parameters such as *SAR*, *SSP*, *RSC*, and *PI* fell within permissible ranges for irrigation water quality. Additionally, most samples met acceptable ranges for

Magnesium Hazard (MH) and Kelley's ratio, essential indicators of irrigation suitability, suggesting favorable conditions for irrigation in most cases.

Positive ion exchange predominates in groundwater, with the evaporation effect significantly influencing ion concentrations. The primary ions detected were alkaline earth metal ions and strong acid ions, contributing to the complex chemical properties of the groundwater. The prevalent water quality type was identified as magnesium sodium sulphate.

In summary, while groundwater in Rural Hyderabad presents challenges due to its complex chemical composition, it remains largely suitable for irrigation with proper management practices. Continued monitoring and management efforts are crucial to sustainably utilize this vital resource for agricultural activities while mitigating potential risks.

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