Geochemical evaluation of groundwater and suitability of groundwater quality for irrigation purpose in an agricultural region of South India

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Abstract
The objective of the present study was to evaluate the geochemical processes controlling the groundwater chemistry and also to assess the groundwater quality suitability criteria for irrigation purposes. An agricultural region of Telangana, South India, was selected for the present study. A total of 100 groundwater samples were collected and estimated for pH, electrical conductivity (EC), total dissolved solids (TDS), calcium (Ca2+), magnesium (Mg2+), sodium (Na+), potassium (K+), bicarbonate (HCO3−), chloride (Cl−), sulfate (SO42−), nitrate (NO3−), and fluoride (F−). The groundwater was characterized by mostly alkaline conditions with a dominance of Na+ and HCO3− ions, indicating the prevailing conditions of weathering and dissolution of silicate minerals. The various geochemical signatures such as Na+ vs Cl−, Ca2+ + Mg2+ vs HCO3−, Ca2+ + Mg2+ vs HCO3− + SO42−, HCO3− vs Cl− + SO42−, Ca2+ + Mg2+ vs total cations, and Ca2+ + Mg2+ vs Na+ + K+ and the saturation indices with respect to calcite, halite, and gypsum suggest obviously the dominant conditions of carbonate weathering associated with the reverse ion exchange and evaporation processes as the geogenic factors. The linear trend of TDS vs NO3− + Cl−/HCO3− clearly specifies the influence of non-geogenic sources on the aquifer system. These are the important contributors to the variation in the groundwater chemistry. However, the impact of the geogenic source is masking the influence of the anthropogenic source in some areas of the present study region. According to the salinity vs sodium adsorption ratio, residual sodium carbonate, magnesium ratio, and Kelly ratio, 99.9%, 7.06%, 63.07%, and 51.27% of the total study region come under the unsuitable categories for irrigation purposes, respectively. Therefore, the findings of this study recommended some site-specific appropriate management strategies for the safe supply of groundwater for proper crop growth and consequently for sustainable development of the rural environment.

Keywords Groundwater chemistry · Groundwater quality · Crop growth · Agricultural region

Introduction

Globally, groundwater is a natural resource for domestic (65%), agricultural (20%), and industrial (15%) purposes (Saeid et al. 2018). Studies on groundwater resources have become vital in semiarid regions for various purposes (Sundraiah et al. 2014; Subba Rao 2017; Faten et al. 2016; Chetan et al. 2017; Laxman et al. 2021; Subba Rao et al. 2021a, b). However, once the groundwater quality becomes an inferior type due to the influences of geogenic and non-geogenic sources, it will not be suitable for any purposes in general (Subba Rao et al. 2021c). The quality of groundwater is controlled by geochemical processes that depend upon the topographical features, flow path, recharge, nature of lithology, and rock weathering associated with mineral dissolution, ion exchange, and evaporation (Li et al. 2013; Saravanan et al. 2015; Subba Rao et al. 2017, 2021a, b). Besides this, increasing exploitation of groundwater, rapid urbanization and industrialization, over-application of chemical fertilizers and pesticides for higher plant growth, animal waste, and improper drainage systems are important human-induced activities, which damage the natural occurrence of...
the chemical quality of groundwater and consequently not only affect human health but also reduce crop production (Deepali et al. 2015; Rahmati et al. 2015; Li et al. 2016a, b; Kouakou et al. 2017; Wagh et al. 2019).

Some recent studies have been exampled here: Contamination was caused by human and agricultural activities that directly and/or indirectly damage the groundwater quality due to the influence of dissolution and transport of excess quantities of fertilizers, and also through the changes in the water–rock reactions in the soils and aquifers in the deltaic region of the Caufvery River in Tamil Nadu, India (Vetrin-rugan and Elango 2014). Because of the dissolution of minerals, evaporation, and non-geogenic impact, the quality of groundwater has considerably deteriorated in the Jazan arid area of Saudi Arabia (Alfy et al. 2015). Groundwater quality was mainly controlled by the lithology, dissolution, precipitation of minerals, and ion exchange in irrigated land on the Southeastern edge of the Tengger Desert, China (Li et al. 2016a). The lithological variation was caused by the changes in the groundwater quality due to the weathering of the rock minerals and evaporation processes in the East Wasit Province, Central Iraq (Ghalib 2017). The chemical weathering of the country rocks associated with the dissolution of minerals and carbonates, and ion exchange, and also man-made pollution mainly were influenced the groundwater quality in Northwestern Tunisia (Ayadi et al. 2018). In Western India, not only the geogenic processes (silicate weathering, ion exchange, and evaporation) as the main governing factors of the chemistry of groundwater, but also the non-geogenic sources (domestic wastes, irrigation-return-flows, and animal wastes) as the secondary sources were damaged the chemical groundwater quality (Wagh et al. 2019). The water–rock interactions with ion exchanges were caused by the inferior groundwater quality for drinking and irrigation purposes in the Lower Ketar Watershed, Ethiopia (Tolera et al. 2020). The water–rock interactions associated with the ion exchange and evaporation as the prime geochemical regulating factors of the geochemical characteristics and also the anthropogenic activities as the secondary factors were caused by the deterioration of the chemical quality of groundwater used for irrigation and drinking purposes in a rural part of Telangana, South India (Subba Rao et al. 2021c).

From the review literature, it can be said that knowledge of the geochemical processes controlling groundwater chemistry is a very important aspect of dealing with groundwater-related issues. The identification of geochemical processes helps in understanding the changes occurring in groundwater quality due to the interaction with aquifer material. On the other hand, understanding the changes in the chemical quality of groundwater caused by human-induced activities like agriculture is also an essential issue, especially in arid and semiarid regions. This type of study in turn assists in management planning for taking the appropriate remedial measures to protect the aquifers from contamination caused by natural (geogenic) and anthropogenic (non-geogenic) origins. Therefore, the geogenic processes and agricultural activities on the aquifer conditions need to be understood everywhere for taking the appropriate suitable measures.

The residents in the State of Telangana, South India, mainly rely on groundwater resources for their drinking and irrigation purposes due to the insufficient supply of surface water sources. The present study region faces the deterioration of the groundwater quality in some places due to the lack of proper awareness on the planning of disposal of household wastes, septic tank leakages, animal wastes, and uncontrolled usage of chemical composites, application of irrigation water flows, etc. As a result, the groundwater quality may not be suitable for drinking purposes as well as for irrigation purposes. However, nobody has so far been carried out any research work from the study region so that the present study would be useful as baseline information for further work in the future. Therefore, the main objective of the present study was to evaluate (a) the weathering processes associated with the ion exchange and evaporation controlling the groundwater chemistry by using the various bivariate diagrams and saturation indices, and (b) the suitability of groundwater quality for agricultural purposes by adopting various irrigation chemical factors like sodium adsorption ratio, residual sodium carbonate, magnesium ratio, and Kelly ratio. This assists in implementing the proper site-specific remedial measures for the sustainable development of society.

Study area

Location

The study region lies between latitude 17°23′–17°25′ N and longitudes 77°45′–78°50′ E in the State of Telangana, South India, covering an area of 632.45 km² (Fig. 1a), which falls in the toposheets of 56 G/15 and 56 G/16 with a scale of 1:50,000 of the Survey of India. The region experiences a dry climate with an average annual temperature of 14 °C (winter) to 41 °C (summer) and an average annual rainfall of about 940 mm. The stream pattern comes under the subdendritic type.

Hydrogeological conditions

The region has a gentle slope. The calcium carbonate concretions are intermixed with soil. The important geological formations are basalts and granite (Fig. 1b). Laterite occurs in patches. The former types are fine-grained with dark-colored rocks, which contain the minerals calcium
plagioclase feldspars and clinopyroxene with olivine, quartz, hornblende, nepheline, orthopyroxene, etc. The latter types are medium- to coarse-grained rocks, which are composed of quartz, plagioclase and potassium feldspars, biotite, apatite, hornblende, etc. These rocks are hard. However, the basalts become water-bearing formations due to the occurrence of vesicular structures, cracks, and joints in them, while the granites become aquifer formations due to the presence of weathered and fractured rock portions. Though the laterites are porous, they are poorly permeable. Groundwater exists under the unconfined to semi-confined conditions. The depth of groundwater level varies from about 18–28 m below ground level. In some areas, the taste of the groundwater quality appears to be slightly brackish due to the influence of the anthropogenic sources (domestic waste, septic tank spillages, irrigation-return-flows, chemical fertilizers, animal wastes, etc.) on the groundwater system, which was observed during the field work.

**Materials and methods**

**Sampling and analytical procedure**

Sampling was carried out in the present study region during the summer month of May 2015. A hundred groundwater samples were collected (Fig. 1a) in one-liter polythene bottles. They were cleaned with 1:1 dilute HCl and washed away with distilled water three times before the sampling, following the standard field procedures suggested by APHA (2012).

The hydrogen ion concentration (pH) and electrical conductivity (EC) were estimated in the field, using their portable meters (Hanna H-198130). Total dissolved solids (TDSs) were computed, using a formula, SEC × 0.64 (Hem 1991). The chemical parameters, such as calcium (Ca²⁺), magnesium (Mg²⁺), sodium (Na⁺), potassium (K⁺), bicarbonate (HCO₃⁻), chloride (Cl⁻), sulfate (SO₄²⁻), nitrate (NO₃⁻), and fluoride (F⁻), were determined, using the titration, calculation, and flame photometer (Elico CL-378), UV spectrophotometer (Photolab-6600 WTW), and ion-selective electrode (Orion), following the standard water quality methods (APHA 2012). The analytical precision between the ionic concentrations of cations and anions was within the standard limit of ±5%, supporting the data precision (Subba Rao 2017).

**Computation of chloro-alkaline indices**

To assess the role of cation exchange and reverse ion exchange in the aquifer system, the chloro-alkaline indices (CAI-1) and CAI-2) were adopted here (Eqs. 1 and 2) as proposed by Schoeller (1977). A negative index of CA (base ion exchange process) indicates an exchange of Ca²⁺ and Mg²⁺ ions from the groundwater with Na⁺ and K⁺ ions from the aquifer material (Deeapli et al. 2015), whereas a positive index of CA (reverse ion exchange) reflects the adsorption of Na⁺ and K⁺ ions on the aquifer material with the release of Ca²⁺ and Mg²⁺ from the groundwater.
Computation of saturation index

The saturation index (SI) is widely used to envisage the chemical activities of particular minerals in the chemistry of groundwater (Subba Rao et al. 2017). The SI was computed to know the role of evaporation through the evaluation of equilibrium between water and respective minerals (Eq. 3) by comparing the ion activity product (IAP) with the solubility product (Ksp), using the geochemical software PHREEQC (Parkhurst et al. 1999).

If SI exceeds zero, it represents the oversaturation (precipitation) concerning a particular mineral (Subba Rao et al. 2017). If SI is below zero, it indicates the unsaturation (dissolution) in respect of a concerned mineral. If SI is equal to zero, it signifies the saturation (equilibrium) associated with a particular mineral.

Computation of irrigation water quality indices

The suitability of the groundwater quality for irrigation purposes was assessed, using salinity (EC), sodium adsorption ratio (SAR), residual sodium carbonates (RSCs), magnesium ratio (MR), and Kelly’s ratio (KR), as suggested by Kelley (1963), Eaton (1950), Richards (1954), and Szaboles and Darab (1964). These irrigation chemical parameters are widely used in different parts of the world (Faten et al. 2016; Kouakou et al. 2017; Subba Rao et al. 2021b), which were computed following the equations (Eqs. 4–7) and taking the ions in milliequivalents per liter (meq/L).

Application of GIS analysis

In the analysis of GIS, the toposheets were digitized, using ArcGIS 10.7 software to generate the thematic spatial maps for observing the variation in the chemical quality of groundwater. Then, the spatial variation maps were extracted, using inverse distance weighted interpolation tools (Subba Rao et al. 2021b).

Results and discussion

Generalized groundwater chemistry

The pH measured from the groundwater samples of the present study region was between 6.30 and 8.90, and its average was 7.14 (Table 1), indicating mostly alkaline nature (Deepali et al. 2015). The EC, which expresses the level of transmitting capacity of current for the property of the water medium, ranged from 88 to 1600 µS/cm with an average of 454.76 µS/cm, indicating multiple processes taking place in the groundwater system (Subba Rao 2017). The TDS varied from 56.32 to 1024 mg/L, which is an average of 291.05 mg/L controlled by both geogenic and non-geogenic sources (Subba Rao et al. 2017).

Among cations, the Ca²⁺ content was from 8.02 to 152.30 mg/L, being an average of 49.60 mg/L (Table 1). Calcium feldspars are the main source of higher concentration of Ca²⁺ (Subba Rao and Maya Chaudary 2019). The Mg²⁺ was between 2.43 and 92.42 mg/L with an average of 23.53 mg/L. This is mainly attributed to the ferromagnesian minerals (olivine, pyroxene, biotite, etc.) present in the

| Table 1 Summary of the chemical composition of groundwater |
|------------------------|------------------------|------------------------|------------------------|
| Chemical parameters    | Minimum                | Maximum                | Average                |
| pH                     | 6.30                   | 8.90                   | 7.14                   |
| EC (µS/cm)             | 88.00                  | 1600.00                | 454.76                 |
| TDS (mg/L)             | 56.32                  | 1024.00                | 291.05                 |
| Ca²⁺ (mg/L)            | 8.02                   | 152.30                 | 49.60                  |
| Mg²⁺ (mg/L)            | 2.43                   | 92.42                  | 23.53                  |
| Na⁺ (mg/L)             | 3.00                   | 416.00                 | 54.13                  |
| K⁺ (mg/L)              | 1.00                   | 118.00                 | 6.20                   |
| HCO₃⁻ (mg/L)           | 20.70                  | 584.79                 | 147.29                 |
| SO₄²⁻ (mg/L)           | 17.73                  | 425.40                 | 127.52                 |
| NO₃⁻ (mg/L)            | 30.00                  | 166.00                 | 97.90                  |
| F⁻ (mg/L)              | 0.04                   | 585.20                 | 56.27                  |
| pCO₂                   | 0.22                   | 5.41                   | 1.13                   |

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basement rocks, apart from the sources of non-geogenic origin (domestic wastes, septic tank leakages, etc.) (Subba Rao 2021). The Na⁺ ranged from 3 to 146 mg/L, and its average was 54.13 mg/L. This could be due to the influence of sodium feldspars, household wastes, irrigation-return-flows, etc., on the groundwater (Deepali et al. 2020). The K⁺ content varied from 1 to 118 mg/L with an average of 6.20. The potassium feldspars are the chief sources, and the potassium fertilizers are the secondary sources of K⁺ in the groundwater (Subba Rao 2002). The concentrations of groundwater were in the decreasing order of Na⁺ > Ca²⁺ > Mg²⁺ > K⁺. The dominance of Na⁺ in the groundwater indicates the weathering and dissolution of the sources of silicate minerals and anthropogenic origins (Subba Rao and Surya Rao 2010; Subba Rao et al. 2020).

Among anions, the HCO₃⁻ content ranged from 20.70 to 584.79 mg/L with an average of 147.29 mg/L (Table 1). This is a result of the release of the CO₂ into the soil zone due to the consequence of the decay of organic matter and weathering of silicate minerals, apart from the influence of atmospheric CO₂ (Subba Rao et al. 2017). The Cl⁻ was from 17.73 to 425.40 mg/L with an average of 127.52 mg/L. Man-made activities (domestic waste, septic tank spillages, irrigation-return-flows, etc.) could be the chief contributors of Cl⁻ to the groundwater (Laxman et al. 2019). The SO₄²⁻ varied from 30 to 166 mg/L, and its average was 97.90 mg/L, which may be caused by the application of gypsum used for the alternation of soil conditions (Subba Rao et al. 2012a, b). The NO₃⁻ was between 0.04 and 585.20 mg/L with an average of 56.27 mg/L. The influence of sewage waste, septic tank leakage, agricultural compost, and animal waste could be the chief source of NO₃⁻ (Deepali et al. 2015; He et al. 2019). The F⁻ was from 0.22 to 5.41 mg/L, and its average was 1.13 mg/L. The fluoride minerals (fluorite, biotite, hornblende, etc.) and phosphate fertilizers may be the sources of F⁻ in the groundwater body (Deepali et al. 2020; Subba Rao et al. 2020a). The decreasing order of abundance of anions was HCO₃⁻ > Cl⁻ > SO₄²⁻ > NO₃⁻ > F⁻. The higher HCO₃⁻ in the groundwater indicates the prevailing conditions of mineral dissolution in the groundwater system (Subba Rao 2018; Deepali et al. 2021).

**Controlling processes of groundwater chemistry**

The dissolved ions in the groundwater system are derived from geogenic origins (rock-forming minerals) as a chief source (Manikandan et al. 2020). The non-geogenic origin (domestic waste, septic tank spillages, irrigation-return-flows, chemical fertilizers, animal wastes, etc.) may also contribute as a secondary source (Sakram et al. 2019). However, sometimes secondary sources overtake the influence of geogenic origin (Subba Rao et al. 2019). Generally, the relative dominance of dissolved ions in groundwater depends on the sources and solubilities of ions (Hem 1991; Subba Rao 2017).

Since the present study region faces problems relating to the geogenic and anthropogenic activities, it needs an assessment of the sources of dissolved ions in the aquifer system, using the different bivariate diagrams (Na⁺ vs Cl⁻, Ca²⁺ + Mg²⁺ vs HCO₃⁻, Ca²⁺ + Mg²⁺ vs HCO₃⁻ + SO₄²⁻, K⁺ vs Cl⁻ + SO₄²⁻, Ca²⁺ + Mg²⁺ vs total cations, Ca²⁺ + Mg²⁺ vs Na⁺ + K⁺ and TDS vs NO₃⁻ + Cl⁻/HCO₃⁻, ion exchange indices (chloro-alkaline indices of CAI-1 and CAI-2), and saturation indices with respect to calcite, halite, and gypsum for taking the site-specific suitable measures for sustainable development of the rural community. These geochemical signatures have been widely used (Subba Rao et al. 2017; Wagh et al. 2019; Deepali et al. 2020; Manikandan et al. 2020), which are discussed below:

**Geogenic sources**

**Influence of rock weathering on groundwater chemistry**

Rock weathering (or cation exchange) and halite dissolution play a significant role in dissolving the ions in the aquifer system (Eqs. 8 and 9). If the groundwater system received the Na⁺ and Cl⁻ ions by the dissolution of halite, the ratio of these ions would be equal to unity (Deepali et al. 2015; Subba Rao et al. 2017). Excess Na⁺ over Cl⁻ represents the rock weathering or cation exchange, while the excess Cl⁻ over Na⁺ indicates the reverse ion exchange (Subba Rao 2008; Subba Rao et al. 2017). Nine percent of the groundwater sampling points in the present study region fall on the uniline of Na⁺ and Cl⁻ ions (Fig. 2a). This reflects the halite dissolution process. A few sampling points (13%) are found above the theoretical line of Na⁺ and Cl⁻ ions, specifying the rock weathering or cation exchange process. Most sampling points (78%) are observed below the equilibrium of Na⁺ and Cl⁻ ions, which measures the contribution of ions from the reverse ion exchange process as the chief source. Since the present study region experiences a semiarid climate and comes under the agricultural area, it leads not only to the formation of soil salts (NaCl, CaSO₄, etc.) but also adds ions associated with the Na⁺ and Cl⁻ to the groundwater body through the application of irrigation-return-flows (Subba Rao et al. 2012a, b). Because Cl⁻ is a non-geogenic origin (Subba Rao 2014), the excess Cl⁻ ion over the Na⁺ ion can also be considered as a source of non-geogenic origin.

\[
\text{(Na}^+ + \text{K}^+ + \text{Ca}^{2+} + \text{Mg}^{2+}) \text{silicates} + \text{H}_2\text{CO}_3 \rightarrow \text{Na}^+ + \text{K}^+ + \text{Ca}^{2+} + \text{Mg}^{2+} + \text{HCO}_3^- + \text{H}_2\text{SiO}_4 + \text{clay product} \\
\text{(8)}
\]

\[
\text{NaCl Halite dissolution} \rightarrow \text{Na}^+ + \text{Cl}^- \\
\text{(9)}
\]
The diagram $\text{Ca}^{2+} + \text{Mg}^{2+}$ vs $\text{HCO}_3^−$ is frequently used to confirm rock weathering or cation exchange as the dominant controlling process of groundwater quality (Sakram and Admilla 2018; Vinnarasi et al. 2021). Above 1:1 equiline of $(\text{Ca}^{2+} + \text{Mg}^{2+})$ and $\text{HCO}_3^−$ indicates the dominance of $\text{Ca}^{2+}$ and $\text{Mg}^{2+}$ ions over the $\text{HCO}_3^−$ caused by rock weathering or cation exchange, and below it confirms the release of $\text{HCO}_3^−$ into the groundwater caused by feldspar minerals with carbonic acid ($\text{H}_2\text{CO}_3$; Eq. 8). In the present study region, 8% of the plotted points are observed below the uniline of $(\text{Ca}^{2+} + \text{Mg}^{2+})$ and $\text{HCO}_3^−$ (Fig. 2b). This indicates that the $\text{Ca}^{2+}$, $\text{Mg}^{2+}$, and $\text{HCO}_3^−$ ions are derived from the dissolution of carbonate rocks, which is further supported by the plotting of the groundwater samples that move toward $\text{HCO}_3^−$ from the theoretical line of $\text{HCO}_3^−$($\text{Cl}^− + \text{SO}_4^{2−}$; Fig. 3a). The maximum plotting points (92%) of the chemical data of the groundwater samples between $(\text{Ca}^{2+} + \text{Mg}^{2+})$ and $(\text{HCO}_3^− + \text{SO}_4^{2−})$ also show the deviation from the equiline and run toward $\text{HCO}_3^− + \text{SO}_4^{2−}$ (Fig. 3b), indicating an excess of $\text{HCO}_3^−$. Generally, the dissolution of $\text{Ca}^{2+}$ and $\text{Mg}^{2+}$ silicates and $\text{HCO}_3^−$ and $\text{SO}_4^{2−}$ associated with the soils give an equal amount of these ions in the groundwater system (Deepali et al. 2021). High $\text{Ca}^{2+} + \text{Mg}^{2+}$ compared to $\text{HCO}_3^−$ indicates the reverse ion exchange due to the derivation of $\text{Ca}^{2+}$ and $\text{Mg}^{2+}$ ions from the aquifer material. If excess $(\text{HCO}_3^− + \text{SO}_4^{2−})$ over $(\text{Ca}^{2+} + \text{Mg}^{2+})$ reveals the removal of $\text{Ca}^{2+}$ and $\text{Mg}^{2+}$ ions from the water by the cation exchange process, or excess $\text{HCO}_3^−$ that is added to the groundwater body by weathering of $\text{Na}^+$ and $\text{K}^+$ silicates (Wagh et al. 2019), apart from the soil $\text{CO}_2$ released from the decay and decomposition of organic matter (Eqs. 10 and 11).

Further, the computed partial pressure of carbon dioxide ($\text{PCO}_2$) in the groundwater samples of the present study region varied from $−3.05$ to $−0.43$ with an average of $−1.18$ (Table 1), which is more than the atmospheric $\text{PCO}_2$ ($−3.50$). The higher $\text{PCO}_2$ of the groundwater indicates the prevailing conditions of the open system weathering with a relatively higher rate of solubility (Vinnarasi et al. 2021). Therefore, the groundwater of the present study regions shows a higher concentration of $\text{HCO}_3^−$ (Table 1).

$$\text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{H}_2\text{CO}_3$$ (10)

$$\text{H}_2\text{CO}_3 \rightarrow \text{H}^+ + \text{HCO}_3^−$$ (11)

Further, it is also noted that most groundwater sampling points in the plots of $(\text{Ca}^{2+} + \text{Mg}^{2+})$ vs $(\text{Na}^+ + \text{K}^+)$ move toward $\text{Ca}^{2+} + \text{Mg}^{2+}$ (Fig. 4a), so that they appear as the major contributors, which exceeds the $\text{Na}^+$ and $\text{K}^+$ ions in the groundwater (Subba Rao et al. 2006). All chemical points of the groundwater samples in the diagram of

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**Fig. 2** Ionic relations a **Na**$^+$ vs Cl$^−$ and b $(\text{Ca}^{2+} + \text{Mg}^{2+})$ vs $\text{HCO}_3^−$

**Fig. 3** Ionic relations a $\text{HCO}_3^−$ vs (Cl$^− + \text{SO}_4^{2−}$) and b $(\text{Ca}^{2+} + \text{Mg}^{2+})$ vs $(\text{HCO}_3^− + \text{SO}_4^{2−})$
(Ca$^{2+}$ + Mg$^{2+}$) vs total cations (Ca$^{2+}$ + Mg$^{2+}$ + Na$^{+}$ + K$^{+}$) also deviate from the equiline and change their trend toward the total cations (Fig. 4b). This is a result of the total contribution of the cations from the source (Subba Rao 2008). Therefore, these diagrams clearly explain the carbonate weathering as the major controlling process of groundwater chemistry due to the occurrence of soil CO$_2$.

### Influence of ion exchange process on groundwater chemistry

As discussed earlier, the excess Cl$^-$ ion over the Na$^+$ ion in the majority (78%) of the groundwater samples (Fig. 2a) explains the reverse ion exchange process taking place in the aquifer system. To verify this phenomenon further in the groundwater of the present study area, the chloro-alkaline indices (CAI-1) and CAI-2) were computed (Eqs. 1 and 2) and the results are shown in Table 2. The values of CAI-1 varied −3.64 to 0.94 with an average of 0.12, while those of CAI-2 were from −0.78 to 3.36 with an average of 0.34. They demonstrated in Fig. 5 representing the cation ion exchange (Eq. 12) and reverse ion exchange processes (Eq. 13). From Fig. 5, it is noted that 83% of the groundwater sampling points fall toward the positive indices of CAI-1 and CAI-2. It enlightens the reverse ion exchange as the chief controlling process in the groundwater system (Deepali et al. 2015).

$$2\text{Na}^+ + \text{CaX}_2 \rightarrow \text{Ca}^{2+} + 2\text{NaX}$$  \hspace{1cm} (12)

$$\text{Ca}^{2+} + 2\text{Na}^+ \rightarrow 2\text{Na}^+ + \text{X}_2$$  \hspace{1cm} (13)

### Influence of evaporation process on groundwater chemistry

The soils in the present study region contain calcium carbonate concretions, which suggest the prevailing conditions of the semiarid climate. As stated above, evaporate dissolution (halite) occurs in the groundwater system. Thus, it is also essential to confirm the role of the evaporation process in the groundwater body. Saturation indices (SI) were computed concerning calcite (CaCO$_3$), halite (NaCl), and gypsum (CaSO$_4$), using Eq. 3. The results are shown in Fig. 6. They predict the reactive minerals with the help of the chemistry of groundwater (Deepali et al. 2015). All groundwater samples show negative values of SI concerning halite (−8.77 to −5.61 with an average of −7.01) and gypsum (−2.45 to −1.22 with an average of −1.90), indicating their unsaturation (dissolution) state. Twenty-six percent and 74% of the groundwater samples show negative and positive values of SI concerning calcite (−1.73–0.67 with an average of −0.71), representing the unsaturation and oversaturation (precipitation) states, respectively. This further supports the occurrence of calcium carbonate concretions in the present study area.

### Non-geogenic source

The present study region is a part of an agricultural rural area and also shows poor disposal conditions for

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**Table 2** Particulars of chloro-alkaline index (CAI), situation index (SI), and irrigation index (II)

| Chloro-alkaline index (CAI) | Minimum | Maximum | Average |
|----------------------------|---------|---------|---------|
| CAI-1                      | −3.64   | 0.94    | 0.12    |
| CAI-2                      | −0.78   | 3.36    | 0.34    |

| Saturation index (SI)      |         |         |         |
|----------------------------|---------|---------|---------|
| Halite                     | −8.77   | 5.61    | −7.01   |
| Gypsum                     | −2.45   | 1.22    | −1.90   |
| Calcite                    | −1.73   | 0.67    | −0.71   |

| Irrigation index (II)      |         |         |         |
|----------------------------|---------|---------|---------|
| EC                         | 88.00   | 1,600.00| 454.76  |
| SAR                        | 0.13    | 6.71    | 2.21    |
| RSC (meq/L)                | −4.22   | 8.01    | 0.14    |
| MR                         | 4.86    | 81.10   | 44.79   |
| KR                         | 0.06    | 8.09    | 1.21    |
household waste and septic tank spillages, animal waste, unlimited use of irrigation-return-flows and agricultural fertilizers, etc. Generally, they modify the groundwater chemistry due to the adding of additional concentrations of ions and thereby inferior groundwater quality occurs. To know the influence of non-geogenic sources on the chemistry of groundwater, the relationship of TDS and $(\text{NO}_3^- + \text{Cl}^-/\text{HCO}_3^-)$ is widely used (Li et al. 2019; Subba Rao et al. 2021c). This relation illustrates a linear trend ($y = 0.0077x + 1.9265$ and $R^2 = 0.1066$; Fig. 7) obviously supporting the influence of the non-geogenic sources on the groundwater system. As a result, the impact of the
anthropogenic source is masking the influence the geogenic source. This is the main reason that the groundwater quality in some areas in the present study region appears to be slightly brackish, depending upon the hydrogeological environmental conditions.

Groundwater quality for crop growth

Salinity (EC) vs Sodium adsorption ratio (SAR)

In the present study region, groundwater is the main source of crop growth. However, its poor quality reduces crop growth considerably (Aravinthasamy et al. 2020). Hence, the assessment of the suitability of the groundwater quality is essential for taking management measures to ensure healthy crop growth (Ghalib 2017). Groundwater salinity expressed in terms of EC plays a significant role in crop growth. The salinity of groundwater is classified as low, C1 (EC < 250 μS/cm), medium, C2 (250–750 μS/cm), high, C3 (750–2250 μS/cm), and very high, C4 (> 2250 μS/cm). With the increase in the groundwater salinity, crop production can be reduced (Subba Rao 2017). The sodium adsorption ratio (SAR) evaluates the influence of the Na+ content about Ca2+ and Mg2+ (Eq. 4), which is expressed in terms of alkalinity. If SAR increases, it reduces soil permeability, which has adverse effects on crop growth (Subba Rao 2018; Subba Rao et al. 2021c).

The SAR is classified as low, S1 (< 10), medium, S2 (10–18), high, S3 (10–28), and very high, S4 (> 28) (Subba Rao 2017). The EC ranged from 88 to 1600 μS/cm with an average of 454.76 μS/cm (Table 1), while the SAR varied from 0.13 to 6.71 with an average of 2.21 (Table 2). Based on the EC vs SAR, 0.10%, 29.83%, and 70.07% of the total study region fall into the zones of the C2S1, C3S1, and C3S2, respectively (Fig. 8). They represent the good (isolated patch), poor (northern, eastern, and isolated patches in western parts), and very poor (northern, central and southern parts) groundwater quality for irrigation purposes, respectively.

Residual sodium carbonate

Residual sodium carbonate (RSC) is also used to evaluate the groundwater suitability for crops, which is a relationship between CO₃²⁻ + HCO₃⁻ and Ca²⁺ + Mg²⁺ (Eq. 5). The RSC is classified into three types (Alaya et al. 2014). They are suitable (< 1.25 meq/L), marginally suitable (1.25–2.50 meq/L), and unsuitable (> 2.50 meq/L) types for irrigation purposes. The RSC varied from −4.22 to 8.01 meq/L, and its average was 0.14 meq/L (Table 2). According to the classification of RSC, the suitable, marginally suitable, and unsuitable types are observed in the areas of 86.24%, 6.70%, and 7.06%, respectively, for irrigation purposes (Fig. 9a). The unsuitable groundwater quality is observed from the eastern part of the study region.

Magnesium ratio

Generally, Mg²⁺ damages the soil structure, when the water has higher Na⁺ and salinity, which decreases the crop yields. The magnesium ratio (MR) was computed, using Eq. 6 (Szaboles and Darab, 1964). The MR was between 4.86 and 81.10, and its average was 44.79 (Table 2). If MR is higher than 50% in water, it is harmful to irrigation, and if it is less than 50%, it is suitable for irrigation purposes (Faten et al. 2016; Subba Rao 2017). Accordingly, 36.93% and 63.07% of the spatial areas come under the suitable and non-suitable types for irrigation purposes, respectively (Fig. 9b). Groundwater quality is observed to be unfit for irrigation purpose from the areas of the central part spreading from western to eastern side of the study region.

Kelly’s ratio

Kelly’s ratio (KR) is used to assess the irrigation water quality (Kelley 1963), which measures the levels of Ca²⁺ and Mg²⁺ ions (Eq. 7). If KR is below one, it is suitable for irrigation, and if it is above one, it is not suitable for irrigation purposes (Aravinthasamy et al. 2020). The KR was from 0.06 to 8.09 with an average of 1.21 (Table 2). As per the classification of KR, 48.73% and 51.27% of the study region fall into the suitable and unsuitable water quality types for irrigation purposes, respectively (Fig. 9c). The unsuitable groundwater quality zone for irrigation purpose is mainly observed from the southern part of the study region.
Recommendations for groundwater quality management

According to the EC vs SAR, RSC, MR and KR, 99.9%, 7.06%, 63.07%, and 51.27% of the total study region come under the poor groundwater quality type for irrigation purposes. These zones spread mainly in the whole area, eastern, central, and southern parts, respectively. The quality of groundwater in these zones may not support crop yields due to the reduction in the soil permeability (Subba Rao et al. 2012a, b, 2021c). Thus, the plant roots are unable to receive water properly and, consequently, nutrients from the soils. Therefore, the following site-specific suggestions are recommended for the sustainable development of groundwater
resources for proper crop growth and consequently for better living conditions of the rural community.

- Inferior groundwater quality should not be used for crop growth without treatment,
- Application of gypsum as an amendment is necessary to increase the soil permeability for proper plant growth,
- The quality of groundwater should be improved through the implementation of the rainwater recharging strategies in the entire study region,
- Drainage systems and septic tanks should be maintained properly to reduce groundwater pollution, especially where the build-up areas occur,
- Biological treatment plants and recycling of solid waste are necessary for a clear and clean rural environment, particularly where the population is more, and
- Creating public awareness on environmental issues must be needed for building a healthy society.

**Conclusions**

The following important conclusions were drawn from the present study region of Telangana, India, after observing the geochemical processes controlling the chemistry of groundwater chemistry, using the various geochemical ratios, and groundwater quality suitability, using the irrigation chemical parameters:

- The groundwater was mostly alkaline with a characterization of Na$^+$ and HCO$_3^{-}$ ions.
- The geochemical ratios such as Na$^+$ vs Cl$^-$, Ca$^{2+}$ + Mg$^{2+}$ vs HCO$_3^{-}$, Ca$^{2+}$ + Mg$^{2+}$ vs HCO$_3^{-}$ + SO$_4^{2-}$, HCO$_3^{-}$ vs Cl$^-$ + SO$_4^{2-}$, Ca$^{2+}$ + Mg$^{2+}$ vs total cations, and Ca$^{2+}$ + Mg$^{2+}$ vs Na$^+$ + K$^+$ and the saturation indices of calcite, halite, and gypsum suggest that the groundwater chemistry was mainly controlled by carbonate weathering associated with the reverse ion exchange and evaporation processes as the geogenic factor. The ratio TDS vs NO$_3^{-}$ + Cl$^{-}$/HCO$_3^{-}$ indicated the non-geogenic origin as the secondary source in the groundwater system. The impact of the latter source is masking the influence the first source in some areas of the present study region.
- As per the groundwater salinity vs sodium adsorption ratio, residual sodium carbonate, magnesium ratio, and Kelly ratio, 99.9%, 7.06%, 63.07%, and 51.27% of the spatial study region were unsuitable for irrigation purposes, and
- Site-specific appropriate management measures were suggested to improve the groundwater quality for proper crop production and consequently for better living conditions of the rural community.

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**Declarations**

**Conflict of interest** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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