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Characterization of Groundwater Quality in the Transitional Plain of Luni Basin and its Suitability for Agricultural Uses

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Abstract: Groundwater quality was assessed for irrigation purposes by collecting groundwater samples from 113 locations during pre-monsoon seasons in Jalore district (Rajasthan). These groundwater samples were analyzed for physico-chemical parameters like pH, EC, TDS, major cations, and anions. Furthermore, irrigation quality indices like salinity hazard, chloride hazard, carbonate and bicarbonate hazard and sodium hazard were calculated using the analytical results. These parameters were compared with standard limits for irrigation use for the prevailing crops. Generally, hydrochemical results indicate that the groundwater in the study area is neutral to very strongly alkaline in nature. Based on the EC classification, most of the groundwater samples are falling under the high to very high salinity hazard category. The order of abundance of major cations and anions in groundwater was found as $Na^+ > Ca^{2+} + Mg^{2+} > K^+$ and $Cl^- > SO_4^{2-} > HCO_3^- > CO_3^-$. Based on the EC and SAR, classification >60% of the samples is falling under the moderate to a high reduction in infiltration rate category. In addition, the study also emphasized that the practice of very high saline and moderately sodic groundwater for irrigation may cause soil salinity as well as sodicity in soils. The study found that the majority of the groundwater samples are above the minimum irrigation water quality standards, suggesting that necessary action is required for sustainable crop production by using appropriate management practices in the area.

Key words: Salinity, EC, TDS, sodicity, SAR, RSC, correlation.

Water is a necessity in almost every aspect of life. Groundwater has become the primary source of water in the agricultural sector in many countries where climate change, rapid population growth, and insufficient river water and drainage systems are viewed as major issues (Rawat *et al*., 2018). The availability of good quality water plays a vital role in national development. Our country has plenty of water in the form of groundwater, which is considered to be a major source of water for domestic, agricultural and industrial uses, but its quantitative availability per person is getting decreased continuously besides degradation in its quality. Groundwater will continue to play an important role in meeting water needs for irrigation and related fields in the coming century (Hopkins *et al*., 2007). The up-surging population and limited natural resources have exacerbated problems associated with wastewater disposal and groundwater exploitation for domestic, industrial, and agricultural purposes.

Groundwater quality degrades twofold: first, due to geochemical reactions in the aquifers and soils and second, when it is supplied through improper canals/drainages for irrigation. As a result, regular assessments of irrigation and drinking water quality are required (Gupta *et al*., 2009; Jacintha *et al*., 2017; Rawat *et al*., 2018). Irrigation necessitates a sufficient supply of usable quality water. The index based on the composition and concentration of dissolved elements in water can help determine its suitability for agricultural use (Singh *et al*., 2013 and 2015). The concentration and composition of dissolved constituents in water determine its quality for irrigation uses. Quality of water used for irrigation governs the rate and degree of development of soil salinity or alkali condition in an irrigated area in arid and semi-arid regions particularly the Thar Desert areas of Rajasthan, Gujarat, Haryana and Punjab, where groundwater is available but the quality is questionable or unsatisfactory. Such areas have limited supplies of surface water and have low rainfall. Thus, the use of groundwater is essential to grow crops, and the management of poor-quality water would play an important role.

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Generally, water quality parameters (major cations as Na^+, Ca^{2+}, Mg^{2+}, K^+) and anions Cl^-, SO_4^{2-}, HCO_3^-, CO_3^{2-}) are indicators of drinking water and irrigation use, while water quality indices such as salinity (EC), sodium adsorption ratio (SAR), sodium percentage (SSP), residual sodium carbonate (RSC), residual alkalinity (RSC), Kelly's ratio/index (KR or KI), permeability index (PI) and potential salinity (PS), based on primary water quality parameters are frequently used to the determine quality of water for irrigation (Singh *et al.*, 2015; Gautam *et al.*, 2015).

One hundred thirteen under groundwater samples were collected from the Luni basin areas of the Jalore district (Rajasthan) and analysed as well as assessed for the characterization of under groundwater samples and their suitability for irrigation purposes in the current study. The main objective of the present research work is to characterize the underground water in Jalore district, to know the salinity, sodicity, residual sodium carbonate (RSC) and its suitability for irrigation purposes.

Irrigation and groundwater resources are inextricably linked. This paper describes the groundwater quality status for irrigation purposes using a water quality index (EC, SAR, SSP, RSC, PI, CR, KR) based on primary parameters (such as K^+, Ca^{2+}, Cl^-, Na^+, Mg^{2+}, SO_4^{2-}, CO_3^- and HCO_3^-). Therefore, the aim of the study was to determine the suitability of groundwater for irrigation.

Material and Methods

Study area

Jalore district is located in the southern part of arid western Rajasthan between 24.6° to 25.8°N latitude and 71.2° to 73.1°E longitude with an area of 10,640 km^2. The district experiences an arid climate and receives an average annual rainfall of 405 mm during monsoon months of June to September.

The transitional plain of Luni basin: The western plain covers a large part of Rajasthan in the west and the northwest of the Aravalli axis. Its northern boundary is marked by Punjab and the southwest by Gujarat and the western boundary is the international boundary between India and Pakistan. The eastern boundary of the western sandy plain is marked by the Aravalli range's. The surface of western Rajasthan is covered with vast stretches of sand occasionally interrupted by rocky protruding right up to the Pakistan border. The Northwestern division is sandy, poorly watered and sterile. The Rajasthan desert in the west has been subdivided into several natural regions because of the Aravalli hills and the rocky terrain of the Barmer-Jaisalmer-Bikaner tract.

The Jalore district forms a part of the Central Luni Basin and is drained by the Luni drainage system, which passes only through the southwestern tip of the district near Sanchore before shedding its load into Runn of Kutch, originating from the Aravalli hill ranges. The ephemeral rivers such as Bandi, Jawai, Khari, Sagi and their major and minor present and prior channels from the drainage system of the district. The major river by and large flow in the east-to-west direction and follow the main structural trends of the rock masses whereas their tributaries follow the major and minor joints and flow in the northwest to the southwest, north-to-south and east-to-west directions. The average annual rainfall (1971-2012) of the district is 445.4 mm. However normal rainfall for the period 1901 to 1970 is 400.6 mm. The annual rainfall gradually decreases from the southeastern part to the northwestern part.

The geological set-up of the district is represented by Quaternary alluvium and various igneous and meta-sedimentary rocks. Younger Alluvium mainly occurs along river courses and stream channels. Groundwater occurs under the unconfined condition in the saturated zone of rock formation. Its occurrence is controlled by topography, physiography and structural features of the geological formations. The movement of the ground water in hard rock areas is governed by size, openness, interconnection and continuity of structurally weak planes while in unconsolidated rocks, ground water movement takes place through pore space between grains. The district is characterized by a landscape of alluvial plains of hill ranges, and isolated hillocks. Jalore district has almost an even topography in its western section, the lowest point being around 17.0 meters above mean sea level and is marked by sand dunes.

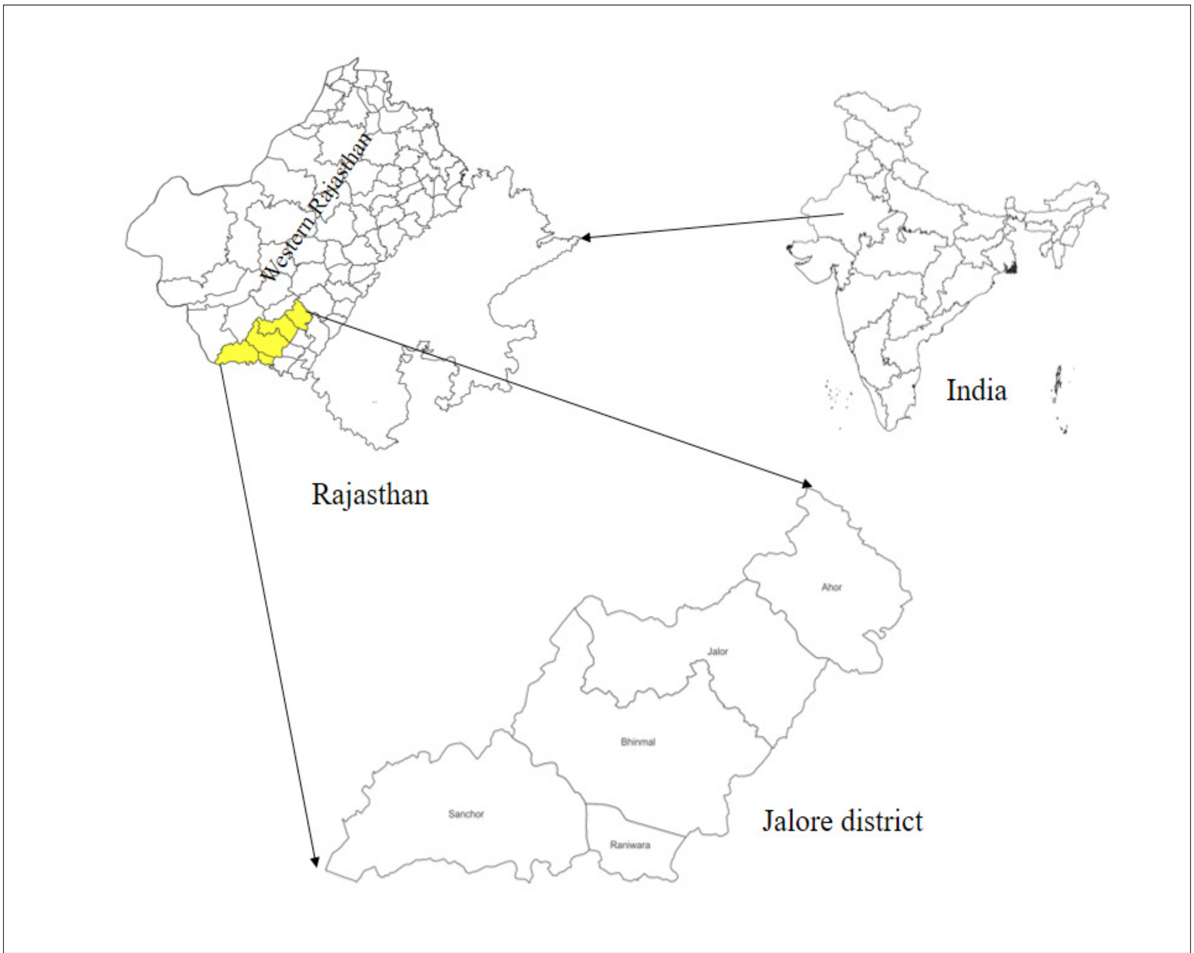

Fig. 1: Groundwater sampling location.

Soils are shallow with deep gravel encrusted with $CaCO_3$. The texture of the soils in general varies from sandy to sandy loam but in deltaic areas of the Luni River south to southwest of Sanchore, the soils are loamy alluvium. The pH value ranges from 7.0 to 9.0 and in general, the soils have a higher pH. The nature of the soils can be broadly described as fine-sorted sand on the dunes and coarse to medium-textured soils on the plains with a tendency for an increase in fine particles. The soils in the eastern part of the district are shallow, covering partly weathered rocks and calcareous gravelly material. Soils along the hill slopes are also mostly shallow consisting of weathered rock and calcareous gravelly materials. The fertility status of the soils in general is low and the proportion of organic matter varies from 0.2 to 1.0%.

In order to characterise the underground water in the Luni basin area of Jalore district for its distribution of salinity-sodicity and suitability for irrigation, 113 geo-referenced underground water samples were collected (Fig. 1 and 2). These water samples were analysed using standard methods and interpreted by using different indices for salinity-sodicity and suitability for irrigation.

Laboratory analysis

The water samples were tested and the analysis was based on standard methods for the examination of water. Water samples were analyzed for cations and anions using the standard method (Richards, 1954). The Ca^{2+} and Mg^{2+} were analyzed Versenate titration method, Na and K by flame photometer and Cl^-, SO_4^{2-}, CO_3^{2-}, HCO_3^- by standard titration methods.

Irrigation water quality assessment

The following parameters such as EC, cations (Na^+, Ca^{2+}+Mg^{2+}, K^+), anions (Cl^-, HCO_3^-, CO_3^-, SO_4^{2-}) were tested in groundwater samples. Irrigation water quality was calculated by TDS, SAR, KR, SSP, PS and EC, to classify the

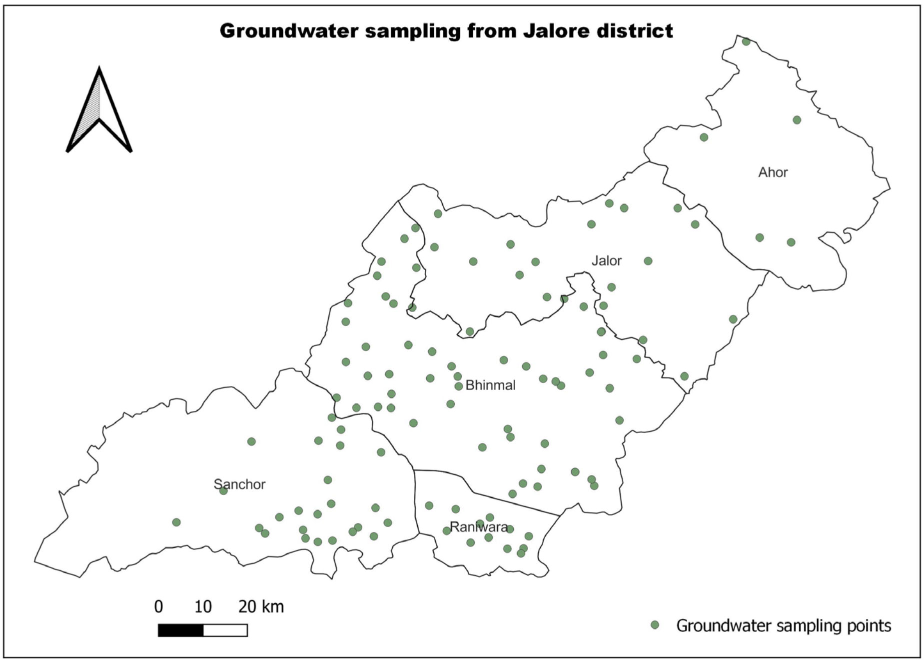

Fig. 2. Groundwater sampling in Jalore district (n=113).

suitability of groundwater for irrigation use as follows:

Total dissolved solids (TDS): Electrical conductivity of groundwater (ECw; dS m^{-1}) value convert to TDS (ppm) by multiplying ECw by an appropriate conversion factor. Conversion factor 640 taken when ECw is <5.0 dS m^{-1} and conversion factor 750 taken when ECw is >5.0 dS m^{-1}.

Sodium adsorption ratio (SAR): *SAR* was used to estimate the potential of Na^+ to accumulate in the soil primarily (water movement) at the expense of Ca^{2+} and Mg^{2+} because of the regular use of sodic water (Bhat *et al*., 2016). Richard (1954) has classified water on the basis of sodium absorption ratio (SAR). SAR is an important parameter for the determination of soil alkalinity or alkali hazards in the use of groundwater for agricultural applications (Srivastva and Ramanathan 2008). SAR is calculated and classified as follows:

$$SAR = \frac{Na^+}{\sqrt{Ca^{2+} + Mg^{2+}/2}} \quad (1)$$

where: Na^+–sodium, Ca^{2+}–calcium, and Mg^{2+}–magnesium, all in miliequivalents per liter (meq L^{-1}).

Residual sodium carbonate (RSC): Richard has also determined the hazardous effect of carbonate and bicarbonates on water quality (Srivastva and Ramanathan, 2008) and classified the water for irrigation purposes in terms of residual sodium carbonate (RSC). It can be determined by a formula as follow:

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

where, all ionic concentrations are expressed in terms of miliequivalents per liter (meq L^{-1}) unit.

Kelly's ratio (KR): Kelly (1963) introduced another factor to assess quality and classification of water for irrigation purpose based on the concentration of Na^+ against Ca^{2+} and Mg^{2+}. It can be calculated using Eq. (3)

$$KR = \frac{Na^+}{Ca^{2+} + Mg^{2+}} \quad (3)$$

KR >1 indicates an excess level of Na^+ in waters. Therefore, water with a KR <1 has been recommended for irrigation, while water with KR >1 is not recommended for irrigation due to alkali hazards (Ayers and Westcot, 1985).

Sodium percentage (Na%): It was used to determine the salinity level based on the concentration of sodium and potassium against calcium and magnesium. When the concentration of sodium and potassium in water is high, it removes calcium and magnesium ions, which reduces the water movement capacity (Wilcox, 1955). The sodium percentage is calculated and classified as follows:

$$Na\% = \frac{Na^+ + K^+}{Ca^{2+} + Mg^{2+} + Na^+ + K^+} \times 100 \quad (4)$$

Soluble sodium percentage (SSP): It was used to determine the salinity level based on the concentration of Na^+ against Ca^{2+} and Mg^{2+}. A high concentration of sodium against calcium and magnesium in water causes toxicity substances, which results in burned leaves and dead plant tissues (Bhat *et al.*, 2016). SSP is calculated and classified as follows:

$$SSP = \frac{Na^+ \times 100}{Ca^{2+} + Mg^{2+} + Na^+} \quad (5)$$

Permeability index (PI): Doneen (1964) has evolved a formula to measure the soil permeability in terms of permeability index (PI) for assessing the suitability of water for irrigation purposes as given below. Where all ionic concentrations are expressed in terms meq L^{-1}.

$$PI = \frac{Na^+ + \sqrt{HCO_3^-}}{(Ca^{2+} + Mg^{2+} + Na^+)} \times 100 \quad (6)$$

Potential salinity (PS): It is another water quality index that was used to determine the salinity level based on the concentration of chloride and sulfate in the borehole water. A high concentration of chloride against sulfate builds up scales in irrigation water supply which can affect the distribution of water to crops (Vasanthavigar *et al.*, 2010). PS is calculated and classified as follows:

$$PS = Cl^- + 0.05 \times SO_4^{2-} \quad (7)$$

where, Cl^-–chloride and SO_4^{2-}–sulfate, all in miliequivalents per liter (meq/l).

Corrosivity ratio (CR): It proposed by Ryzner (1944) and had been adopted here to explore the utility of PVC pipes for groundwater supply, as described below.

$$Corrosivity\ ratio\ (CR) = \frac{0.028\ Cl^- + 0.021\ SO_4^{2-}}{0.02\ (HCO_3^- + CO_3^-)} \quad (8)$$

Results and Discussion

The concentration and composition of dissolved constituents in groundwater determine its quality for irrigation use. The groundwater samples were analyzed for various chemical parameters, viz., pH, EC, TDS, anions (CO_3^{2-}, HCO_3^-, Cl^- and SO_4^{2-}) and cations (Ca^{2+}, Mg^{2+}, Na^+ and K^+). Subsequently, SAR and RSC were calculated for these samples. The range and mean of different water quality parameters are given in Table 1.

Assessment of groundwater for the irrigation suitability

Due to paucity of surface water for irrigation in the study area, groundwater can be assessed for irrigation suitability. The suitability of water mainly depends upon soil type and its composition, crop pattern, and irrigation practices. They are responsible for changing the chemical characteristics of groundwater. Its' suitability was evaluated using some indices such as salinity, SAR, SSP, KR, RSC and CR etc. as discussed below.

The pH is an important parameter for determining the acidity, neutrality or alkalinity of water. The result revealed that the pH of groundwater (Table 1) samples varied from 7.1 to 10.4 (neutral to very strongly alkaline) with a mean value of 8.0, which indicated that in the study area water resources were moderately alkaline in reaction. The variations in pH are relatively small and the results also show that the alkaline pH is particularly due to bicarbonate and not due to carbonate alkalinity (Ahmad and Qadir, 2011). The higher pH of most of the groundwater samples (pH >8.5 nearly 41%) may be due to considerable sodium, calcium, magnesium, carbonate and bicarbonate concentration (Rao *et al.*, 1982; Al-Tabbal and Al-Zboon, 2012) as carbonates and bicarbonates are hydroxyl generating ions (Bhat *et al.*, 2018). Among water-soluble anions chloride and sulphate varied from 1.2 to 87.0 me L^{-1} and traces to 35.9 me L^{-1}, respectively. Sodium is the dominant cation whose concentration ranged from 1.21 to 197.7 me L^{-1}.

The concentration of cations viz., sodium, calcium+ magnesium and potassium in groundwater samples varied from 1.2 to 197.7, 2.6 to 120.0 and 0.0 to 0.7 me L^{-1} with mean of 28.2, 12.2 and 0.1 me L^{-1} (Table 1). In groundwater samples, the order of cationic abundance (in me L^{-1}) is $Na^+ > Ca^{2+}+Mg^{2+} > K^+$. The high concentrations of sodium may be attributed to a base-exchange reaction and leaching of sodium salts like halite during the movement of water through sediments (Etteieb *et al.*, 2017). Kumar *et al.* (2009) reported that the possible source of sodium concentration in groundwater may be due to the dissolution of rock salts and weathering of sodium-bearing minerals. Jalali (2010) reported that the dissolution of anorthite can also contribute to the Ca^{2+} ions in groundwater. The low levels of potassium in groundwater samples may be ascribed to its tendency to be fixed by clay minerals and to participate in the formation of secondary minerals (Matthess, 1982; Jalali, 2005).

The concentration of anions viz., chloride, carbonate, bicarbonate and sulphate in groundwater samples varied from 1.2 to 87.0, 0 to 5.9, 0.8 to 28.6 and 0.0 to 35.9 me L^{-1} with mean of 20.5, 2.0, 6.9 and 6.8 me L^{-1} (Table 1 and 2). In groundwater samples, concerning anionic chemistry, the order of anionic abundance (in me L^{-1}) is $Cl^{-}>SO_4^{2-}>HCO_3^{-}>CO_3^{-}$. The higher chloride content in the groundwater may be due to natural processes like weathering, dissolution of salt deposits and irrigation drainage return flow (Kumar *et al*., 2009). Also, the source of chloride may be non-lithological in nature (poor sanitary conditions, irrigation-return-flows, chemical fertilizers, etc.). Sulphate in groundwater might be due to the presence of sulphide-bearing minerals and gypsum in aquifer materials, the application of sulphate-rich fertilizers and industrial wastes (Sridharan and Nathan, 2017). Moreover, the application of soil amendments like gypsum is expected to be responsible for higher SO_4^{2-} content in the groundwater. The dominance of bicarbonate ions indicates a mineral dissolution process. The higher concentration of bicarbonate may be ascribed to the reaction of carbonate minerals with carbon dioxide gas (CO_2) and the dissolution of CO_2 from the possible mechanisms (Houatmia *et al*., 2016).

Positive and significant correlation was observed between major cations, Na–Ca+Mg (r=0.69; Table 3) which suggests that the concurrent increase or decrease in cations is due of dissolution/precipitation reaction and concentration effects. A positive correlation was observed between Na^{+} with Cl^{-1} (r=0.88) and SO_4^{2-} (r=0.45) (Table 3) indicating that the excess of Na^{+} in these samples largely results from the dissolution of its chloride and sulphate minerals. There is a positive and significant relationship (r=0.47; Table 3) between Ca^{2+}+Mg^{2+} and HCO_3^{-} which indicates that calcite/dolomite may be the source of Ca^{2+} and Mg^{2+}. The correlation between Cl^{-} and Ca^{2+}+Mg^{2+} (r=0.45; Table 3) implies that a part of the chloride and Ca^{2+}+Mg^{2+} may also be derived by the weathering of Ca-Mg bearing mineral (Jalali, 2010).

Salinity: Generally, groundwater salinity is measured either as total dissolved solids (TDS) or electrical conductivity (EC) value of groundwater. The main ions responsible for the salinity are Na^{+}, K^{+}, Ca^{2+}, Mg^{2+}, and Cl^{-}, etc. Dry condition is the main reason for higher salinity in the soil. Salinity also upsurges due to declining in the water table in dry conditions. Human and industrial activities play a vital role in the enhancement of salinity. Thus, the groundwater salinity was evaluated according to Davis and De-Wiest (1966) and Richards (1954) as presented in Table 1 and 2. Groundwater had been categorized into five categories such as C1: excellent or very low (up to 0.25 dS m^{-1}), C2: good or low (0.25-0.75 dS m^{-1}), C3: fair or medium (0.75-2.25 dS m^{-1}, C4: poor or high (2.25-5.0 dS m^{-1}) and C5: worse or very high (>5.0 dS m^{-1}). Salinity point of view, EC ranged from 0.3 to 12.1 dS m^{-1} (low to very high salinity) with a mean value 3.6 dS m^{-1} (high salinity), which falls under salinity class C4 i.e. very high salinity indicating unsuitability for irrigation (Table 1 and 2). However, out of 113 samples, 11 samples came under C2 class i.e. low salinity class (0.25 to 0.75 dS m^{-1}), 20 samples came under C3 class i.e. medium salinity class (0.75 to 2.25 dS m^{-1}) which might create salinity problems in soils, 54 samples came under C4 salinity class i.e. high salinity class (2.25-5.0 dS m^{-1}) which also might create salinity problems in soil and 28 samples belonged to C5 class i.e. very high salinity class (>5.0 dS m^{-1}) and hence is not advisable to irrigation purposes due to possibility of high salinity development in soil (Table 2). The variation in EC may be ascribed to anthropogenic activities and geochemical processes existing in this region. The correlation matrix of the groundwater samples exhibits excellent positive correlation between EC and cations (Ca^{2+}+ Mg^{2+}, Na^{+}, K^{+}), anions (Cl^{-}, CO_3^{-}, HCO_3^{-} and SO_4^{2-}) and SAR (Table 3).

***Sodium absorption ratio (SAR)*:** The sodium adsorption ratio is the most useful parameter for determining the suitability of groundwater for irrigation. The SAR of soil solution increases

Table 1. Statistical evaluation of groundwater quality parameters of Jalore district by descriptive statistics method (n=113)

Quality parameter	Min	Max	Mean	SD	Variance	Skewness	Kurtosis
pH	7.1	10.4	8.0	0.5	0.2	1.5	6.2
EC (dS m^{-1})	0.3	12.1	3.6	2.5	6.1	0.9	0.7
Na^+ (meq L^{-1})	1.2	197.7	28.2	25.2	633.1	3.1	17.5
Ca^{2+}+Mg^{2+} (meq L^{-1})	2.6	120.0	12.2	14.8	219.6	5.1	30.7
K^+ (meq L^1)	0.0	0.7	0.1	0.1	0.0	2.7	12.2
Cl^- (meq L^{-1})	1.2	87.0	20.5	16.5	271.2	1.1	1.5
CO_3^{2-} (meq L^{-1})	0.0	5.9	2.0	1.2	1.3	0.9	1.1
HCO_3^{2-} (meq L^{-1})	0.8	28.6	6.9	4.1	16.5	1.6	6.2
SO_4^{2-} (meq L^{-1})	0.0	35.9	6.8	8.4	71.0	1.8	2.8
SAR (mmol $L^{-1})^{1/2}$	0.6	33.1	11.6	7.0	48.9	0.3	-0.2
RSC (meq L^{-1})	0.0	5.4	1.1	1.5	2.2	1.1	-0.1
Na%	7.0	89.0	65.7	18.5	341.0	-1.4	1.3
SSP (%)	7.0	88.8	65.2	18.7	348.8	-1.4	1.2
KR	0.1	8.1	2.6	1.5	2.2	0.4	0.4
CR ratio (me L^{-1})	0.5	28.4	4.1	4.0	15.8	3.5	16.1
PS (me L^{-1})	1.2	87.2	20.8	16.6	277.0	1.1	1.4
PI (%)	8.5	94.3	75.3	16.3	266.5	-2.0	4.3

SSP= Soluble sodium percentage; KR = Kelly ratio; CR = Corrosivity ratio, PS = Potential salinity; PI = Permeability index.

as the SAR of irrigation water increases, increasing the soil's exchangeable sodium (Isaac *et al.*, 2009; Bhat *et al.*, 2018). The SAR values helped to classify groundwater as S1: excellent/low (<10), S2: good/medium (10-18), S3: fair/high (18-26) and S4: poor/very high (>26) as suggested by Richards (1954). According to this classification, SAR values ranged from 0.6 to 33.1 with a mean value of 11.6 i.e. from low sodicity class S1 to very high sodicity S4 class (Table 1), which indicated that water came under the medium sodicity class (Table 2). However, the mean value of SAR was 11.6, which fell into the medium sodicity class (S2). 42% of samples belonged to the excellent group (S1 class) i.e. very low sodicity and can be used safely for irrigation purposes, and 42% of samples came under the S2 class i.e. good/medium sodicity class. While, 15% of samples came under the S3 class i.e. high sodicity class and 2% of samples were of the very high sodicity class, which indicated that the development of sodicity might arise in the soil if these waters are taken for irrigation purposes. High SAR values (>10) could cause sodium to replace adsorbed calcium or magnesium, thereby damaging the soil structure. When the concentration of Na^+ is high in irrigation water, sodium ions tend to be absorbed by clay particles, displacing Mg^{2+} and Ca^{2+} ions. The exchange process of sodium in water for magnesium and calcium in soil reduces permeability and eventually results in soil with poor drainage. Hence, air and water circulation is restricted during wet conditions and such soils are usually hard when dry (Collins and Jenkins, 1996; Saleh *et al.*, 1999).

Combination of salinity and sodicity hazard: Combining the salinity class with the sodicity class, the quality of water samples varied from C2S1 to C5S4. Out of 113 samples, 10% of samples came under C2S1 (low salinity with low sodicity class), 18% of samples came under C3S1 (medium salinity with low sodicity class), 12% of samples came under C4S1 (high salinity with low sodicity class), 34% of samples came under C4S2 (high salinity with medium sodicity class), 2% of samples came under C4S3 (high salinity with high sodicity class) and C5S1 (very high salinity with low sodicity class), 8% of samples came under C5S2 (very high salinity with medium sodicity class), 13% of samples came under C5S3 (very high salinity with high sodicity class) and 2% of samples came under C5S4 (very high salinity with high sodicity class). It is evident that C2S1 (medium salinity-low SAR) groundwater can be used to irrigate soil with moderate leaching and only

Table 2. Categorization of groundwater samples for irrigation purposes in Jalore district (n=113)

Parameters	Range	Water classification	Number of samples within the specified range
EC in dS m^{-1} (Richards, 1954; Wilcox, 1955)	<0.25	Excellent (C1)	-
	0.25-0.75	Good (C2)	11 (10)*
	0.75-2.25	Fair (C3)	20 (18)
	2.25-5.0	Poor (C4)	54 (48)
	>5.0	Extreme (C5)	28 (25)
TDS in ppm (Bryan *et al*., 2007)	<160	Very low hazard	-
	160-480	Low hazard	11 (10)
	480-1280	Medium hazard	17 (15)
	1280-1920	High hazard	23 (20)
	>1920	Very high hazard	62 (55)
Chloride (meq L^{-1}) (Ayers and Wescot, 1985)	<2	Low hazard	8 (7)
	2-4	Medium hazard	15 (13)
	4-10	High hazard	11 (10)
	>10	Very high hazard	79 (70)
SAR (Richards, 1954; Todd, 1980)	<10	Excellent (S1)	47 (42)
	10-18	Good (S2)	47 (42)
	18-26	Fair (S3)	17 (15)
	>26	Poor (S4)	2 (2)
Na % (meq L^{-1}) (Wilcox, 1955)	<20%	Excellent to good	5 (4)
	20-40%	Good to permissible	9 (8)
	40-60%	Permissible to doubtful	16 (14)
	60-80%	Doubtful to unsafe	64 (57)
	>80%	Unsafe	19 (17)
SSP in me L^{-1} (Wilcox, 1955; Todd, 1995)	<20	Excellent	5 (4)
	20-40	Good	10 (9)
	40-80	Permissible	80 (71)
	>80	Unsafe	18 (16)
Kelly's ratio (Kelly *et al*., 1940)	<1	Suitable	19 (17)
	>1	Unsuitable	94 (83)
RSC in me L^{-1} (Eaton, 1950; Richards, 1954; Lloyd and Heathcote, 1985)	<1.25	Suitable	77 (68)
	1.25-2.50	Marginal suitable	11 (10)
	>2.50	Unsuitable	25 (22)
Corrosivity ratio (Ryner, 1944)	<1	Suitable	8 (7)
	>1	Unsuitable	105 (93)
Potential salinity in me L^{-1} (Doneen, 1964)	<3.0	Suitable	15 (13)
	>3.0	Unsuitable	98 (87)
Permeability index in me L^{-1} (Doneen, 1964)	Class I	>75% permeability	79 (70)
	Class II	25-75% permeability	30 (27)
	Class III	<25% permeability	4 (4)

*values in parenthesis () expressed in per cent samples.

for those plants which are moderately salt tolerant and can grow without adopting any special practices for salinity control. The result shows that a majority of the groundwaters possess high salinity with medium sodicity class (C4S2) i.e. unsafe for irrigation due to high salinity problem (Table 2), though sodicity problems along with salinity may also arise to certain extent. Hence, the water of C4S2 cannot be used as irrigation water for soils with limited drainage. However, in order to use the water of this site even for the soils with adequate drainage, special management practices for salinity control need to be implemented and only plants with high salt tolerance could be selected. According to Lauchli and Epstein (1990), salinity can affect plant growth and development in a variety of ways, including osmotic effects, specific toxicity, and/or nutritional disorders. Thus, excessive salts can be one of the major problems with water used for irrigation in this area, and the water cannot be used for irrigation with most crops without special conditions for salinity control, such as leaching requirements or cropping of salt-tolerant plants. In this study, about 15% of the water samples fall in high salinity and high sodicity hazard class (~C5S3), with continuous use of such water samples in the long-term, will increase both salinity and sodicity hazard in the soil.

***Residual sodium carbonate (RSC)*:** Water containing an excessive amount of HCO_3^- and CO_3^-, react with Ca^{2+} and Mg^{2+} in soil solution and will precipitate them as calcite and magnesite. This will allow sodium adsorbed to dominate onto the clay surfaces, to enhance the exchangeable sodium percentage (ESP) of soil, which increases sodium hazard and its related problems such as reducing soil permeability, soil aeration, high pH, inhibiting root penetration, etc. (Bohn *et al*., 1985; Domenico and Schwartz, 1990; Todd and Mays, 2005). Thus, some of the researchers have attempted to present equations to show the effects of interactions among Ca^{2+}, Mg^{2+}, Na^+, HCO_3^- and CO_3^{2-} on water quality for irrigation purposes. Eaton (1950) and Richards (1954) suggested that RSC is a good index of the sodicity hazard of irrigation water. RSC values of groundwater ranged from nil to 5.4 me L^{-1} with a mean value of 1.1 me L^{-1} (Table 1). Richards (1954) classified that water having RSC >2.5 meq L^{-1} are not suitable for irrigation, while those having 1.25-2.50 meq L^{-1} are medium and under 1.25 meq L^{-1} are presumably in a safe condition. Negative RSC indicates that accrual of Na^+ is unlikely since sufficient Ca^{2+} and Mg^{2+} are in excess of what can be precipitated as CO_3^{2-}. Continues use of waters having RSC >2.5 meq L^{-1} leads to salt build-up which may hinder the air and water movement by clogging the soil pores and lead to degradation of the physical condition of soil. This RSC pattern clearly indicates the occurrence of alkaline water causes the low permeability of the soil. Water with high RSC has high pH and land irrigated by such water becomes infertile owing to the deposition of sodium carbonate (Eaton, 1950). Based on the classification, RSC data revealed that 68% of groundwater samples came under the category of the permissible/safe group, 10% of samples came under the marginal group and 22% of samples had RSC values >2.5 me L^{-1} i.e. unsafe category (Table 2). Therefore, continued use of alkaline waters for irrigation in a closed system may cause adverse effects on soil physical properties and deteriorate the soil and water characters in the region and also affect the sustainability of crop production in the long run.

***Per cent sodium (Na%)*:** A sodium hazard could result from irrigation waters with a high concentration of Na^+ (Wilcox, 1955). Increased levels of Na^+ in water have detrimental impacts on soil permeability, soil characteristics, and plant growth (Nishanthiny *et al*., 2010). Therefore, while determining whether irrigation water is suitable or not suitable then the examination of %Na is crucial (Wilcox, 1948). The %Na in the study area varies from 7.0 to 89.0 meq L^{-1} with an average value of 65.7 meq L^{-1} (Table 1). Irrigation waters are classified based on %Na alone (Wilcox, 1948), as illustrated in Table 2. As per the Indian Standards (BIS, 2003), a maximum Na^+ content of 60% is recommended for irrigation water. The per cent Na >60% may result in Na^+ accumulations that will cause a breakdown of the soil physical properties (Ramesh and Elango, 2012). Hence, 64% of sampling points falling under between doubtful to unsafe category. When the concentration of sodium ions is high in irrigation water, Na^+ tends to be absorbed by clay particles, displacing magnesium and calcium ions. This exchange process of sodium in water for Ca^{2+} and Mg^{2+} in soil reduces the permeability and eventually results in soil with poor internal drainage.

***Soluble sodium percentage (SSP)*:** According to Nagarju *et al*. (2006) the percentage of soluble sodium in irrigation water is an important parameter in determining soil permeability. Sodium ions in irrigation water are exchanged with Mg^{2+} and Ca^{2+} ions in clay particles. This exchange process reduces soil permeability, causes poor internal drainage, and hardens the soil, all of which have a negative impact on soil quality and seedling emergence (Tijani, 1994). Excess sodium encourages the combination of sodium with chloride and carbonate, which worsens soil salinity and sodicity and has a negative impact on plant growth and crop productivity. Thus, it is essential to classify groundwater in the study area on the basis of soluble sodium percentage (Wilcox, 1955; Todd, 1995) as excellent (<20%), good (20-40%), permissible (40-80%), and unsafe (>80%). The SSP of the samples varied from 7.0 to 88.8% with a mean value of 65.2% in the study area (Table 1). On the basis of this classification, 4 and 9% of samples of Jalore have an excellent and good category, respectively and 71 and 16% of samples had a permissible and unsafe category, respectively. But the majority of samples (~87%) are doubtful to unsafe categories for irrigation use in the study area (Table 2). Similar results was also observed for arid zone of Rajasthan by Gopal *et al*. (1980).

***Potential salinity (PS)*:** Doneen (1964) explained that the suitability of water for irrigation is not dependent on soluble salts. Because the low-solubility salts precipitate in the soil and accumulate with each successive irrigation, the concentration of highly soluble salts increases the soil salinity. Potential salinity (PS) was employed as an indicator to determine the suitability of groundwater for irrigation based on Cl^- and SO_4^{2-} concentration in the groundwater. The potential salinity of the water samples range from 1.2 to 87.2 meq L^{-1} with an average of 20.8 meq L^{-1} (Table 1). As per the classification, potential salinity data shows that 87% of groundwater is not suitable (>3 meq L^{-1}) for irrigation, while 13% is suitable (<3 meq L^{-1}) (Table 2). It suggests that the potential salinity in the groundwater of the studied area nearly is high, thus, making the water unsuitable for irrigation usage.

***Kelly's ratio (KR)*:** KR was used to determine the salinity level based on the concentration of sodium against calcium and magnesium in the borehole water. Calcium serves an important part in plant mineral nutrition. Ca^{2+} ions are frequently replaced by Na^+ ions and are based on the ratio of Na^+ to Ca^{2+} and Mg^{2+}. When an excessive amount of sodium reacts with calcium and magnesium in irrigation water, it causes toxic materials that result in poor water quality, and this affects plant growth rate and yield (Jaji *et al*., 2007). In the present investigation, KR varied from 0.1 to 8.1 with a mean value of 2.6 (Table 1). According to Ayers and Westcot (1985), the KR value of >1.0 in the groundwater sample is commonly viewed as unfit for irrigation. About 83% of samples having values of >1.0 were found to the poor quality for irrigation in the study area (Table 2).

***Corrosivity ratio (CR)*:** Information about the Corrosivity ratio (CR) in groundwater plays a very important role in choosing suitable pipes for supplying water. This CR employs an electrolytic process between water and pipes. When it takes place it severely attacks and corrodes away the metal surface. Most of the problems are generated by salinity. Deposition of scale and sludge on the metal surface is caused by the increased salinity in groundwater. For industrial as well as domestic activities, a calculation of the corrosivity ratio in the groundwater samples is a very important factor. In the study area, groundwater is being extracted for various purposes and unknowingly transported by metallic and/ or PVC pipes, which may not be suitable for transportation. This fact is highlighted using the CR proposed by Ryzner (1944). Groundwater with a corrosivity ratio of less than 1.0 is viewed as safe for the transportation of water through any pipe, while a corrosive ratio of >1.0 is destructive and thus ought not to be transported through any metallic pipe (Mondal *et al*., 2016). It ranged from 0.5 to 28.4 with a mean value of 4.1 (Table 1). Only about 7% of the samples having a corrosivity ratio <1.0 could be transported by any type of pipe and the remaining 93% of samples in the study area having a corrosivity ratio >1.0 required only PVC pipes (Table 2). Therefore, groundwater must be transported by the PVC pipe in these areas.

***Permeability index (PI)*:** On the basis of PI values, groundwater quality can be assessed for its suitability for irrigation purposes (Rawat *et al*., 2018). According to Singh *et al*. (2015) the concentration of Ca^{2+}, Na^+, Mg^{2+} and HCO_3^- influences the permeability of the soil profile. Therefore, these cations and anions are used to calculate PI values of water to evaluate its quality. Xu *et al*. (2019) correlated high PI values

Table 3. Correlation matrix among the chemical constituents of the groundwater (n=113)

	EC	pH	Na^+	TDS	$(Ca^{2+}+Mg^{2+})$	K^+	CO_3^-	HCO_3^-	Cl^-	SO_4^{2-}	SAR	RSC
EC	1.00											
pH	0.03	1.00										
Na^+	0.89**	0.0	1.00									
TDS	0.99**	0.02	0.88**	1.00								
$(Ca^{2+}+Mg^{2+})$	0.41**	0.04	0.69**	0.41**	1.00							
K^+	0.51**	-0.06	0.35**	0.51**	0.05	1.00						
CO_3^-	0.30**	0.21*	0.13	0.29**	-0.16	0.16	1.00					
HCO_3^-	0.58**	0.05	0.71**	0.56**	0.47**	0.19*	0.09	1.00				
Cl^-	0.95**	-0.12	0.88**	0.95**	0.42**	0.50**	0.26**	0.67**	1.00			
SO_4^{2-}	0.66**	0.22*	0.45**	0.66**	0.15	0.34**	0.18	-0.09	0.41**	1.00		
SAR	0.89**	0.03	0.80**	0.87**	0.20*	0.40*	0.31**	0.56**	0.86**	0.56**	1.00	
RSC	-0.11	0.39**	-0.11	-0.13	-0.22*	-0.06	0.11	0.33**	-0.10	-0.27**	0.06	1.00

*Correlation is significant at the 0.05 level (2-tailed); ** Correlation is significant at the 0.01 level (2-tailed).

with high amounts of sodium and bicarbonate ions in groundwater. The high levels of HCO_3^- and Na^+ ions may be due the dissolution of carbonate from calcite and dolomite and the cation exchange process.

Doneen (1964) and Nagaraju *et al*. (2006) classified water quality on the basis of PI into Classes I, II, and III. Class I (>75% PI) and class II (25-75% PI) indicate good water quality for irrigation purposes (water movement freedom is high and moderate in soil, respectively), while Class III (up to 25% permeability; water movement freedom is less in soil) water is unsuitable for irrigation. A high permeability index is associated with subsurface structural features, which facilitate widespread contamination of groundwater. From Table 3, it can be demarcated that the PI values vary from 8.5 to 94.3 with an average of 75.3. As per the PI values, the groundwater samples of the study area fall in Classes I and II (96%) and were described as having excellent to good permeability (Table 2) and the remaining 4% of groundwater samples fall under Class III i.e. groundwater was unsuitable for irrigation. The soil permeability is affected by the extensive use of irrigation water as it influenced by Na^+, Ca^{2+}, Mg^{2+} and HCO_3^- contents of the water (Gautam *et al*., 2015). Nearly 96% water samples fall into the Class I and II Category of Donnen's chart and are categorized as good for irrigation.

Pearson's correlation matrix: The Pearson correlation matrix (Table 3) is used to recognize the relationship between different variables. A significant positive correlation was noticed between electrical conductivity and cations-anions. Significant positive correlation was noticed between EC-TDS (r = 0.99), EC-Na^+ (r = 0.89), EC-Cl^- (r = 0.95), EC-potential salinity (r=0.95) and EC-SAR (r = 0.89) which revealed that the presence of salinity, Na^+ and Cl^- ions was strongly correlated with EC and TDS. Significant positive and negative correlation was observed between RSC-HCO_3^- (r=+0.33) and RSC-$Ca^{2+}+Mg^{2+}$ (r=-0.22), respectively.

A significant positive correlation between EC and EC-$Ca^{2+}+Mg^{2+}$ (r = 0.41), K^+ (r=0.51), and SO_4^{2-} (r = 0.66) shows that these ions are contributing significantly to EC (Keesari *et al*., 2016 and suggest that significant anthropogenic activities are responsible for the addition of these ions into the groundwater of the region (Ahamad *et al*., 2018). Significant positive correlation between EC-SAR (r=0.89); pH-RSC (r=0.39)

The various indices presented above substantially confirm that the percentage of the unsuitability of under groundwater for irrigation is almost 93% corrosivity ratio (CR), 87% potential salinity (PS), 73% salinity problem (EC) and soluble sodium percentage (SSP), 83% Kelly ratio (KR) and 22% for RSC, 17% sodicity hazard (SAR) and 4% permeability index (PI). This comparison revealed that although Na^+ and Cl^- are dominant among ions, alkali Earth (Ca^{2+} + Mg^{2+}) and carbonate hazards are more prominent for irrigation water quality. The EC, SAR and RSC values hinted that one-third of water samples belong to either moderately

Table 4. Remedial approach using saline, sodic and RSC groundwater for irrigation purpose

Hazard	Class and level	Mitigation/Remedial measures
Salinity (dS m^{-1})	C1: <0.25 (Excellent)	Can be used for most soil for most crops
	C2: 0.25-0.75 (Good)	Can be used with moderate leaching with moderate salt-tolerant crops
	C3: 0.75-2.25 (Fair)	Cannot be used where drainage is restricted, salt-tolerant plants can be grown with careful irrigation (mixing/or alternate use of good quality water), good drainage, and leaching is required
	C4: 2.25-5.0 (Poor)	Unsuitable for irrigation, except for some highly salt-resistant plants, excellent drainage, frequent leaching, and intensive management (mixing/or alternate use of good quality water) required
	C5: >5.0 (Extreme)	Not suitable for irrigation
Sodicity (SAR)	S1 (Low): <10	Sodium sensitive crops can be used cautiously
	S2 (Medium): 10-18	Sodium hazard likely in fine textures soil, Can be used on soils having high permeability. Amendments (such as Gypsum) and leaching is required
	S3 (High): 18-26	Generally unsuitable for continuous use Field bunding for ponding of rainwater and subsequent leaching of salt, Sodic tolerant crops can be taken with low-cost drainage facility using requisite gypsum amendments, addition of organic matter, green manuring like Daincha/Sunhemp etc.
	S4 (very high): >26	Generally unsuitable for use except with highly irrigation management, special management should be taken, Similar remedial measures should be taken like 'S3 hazard' case
RSC water (me L^{-1})	Good: <1.25	Safe for irrigation
	Doubtful: 1.25-2.50	Addition of Ca source as gypsum (Gypsum bed) to neutralize the carbonate/ bicarbonate like the above control measures as mentioned in SAR hazard (S2 and S3)
	Unsafe: >2.50	Unsafe for irrigation, similar remedial measures like the SAR hazard (S4)

saline or moderately unsafe for irrigation purposes and its continuous use may lead to salinity/alkalinity development in soil.

There are a number of ways to improve water quality, with regard to salinity and sodicity hazards, prior to use for irrigation purposes. High salinity and chloride hazards may reduce the crop production and growth; which may require careful management and special type of irrigation practices to avoid crop failures. The majority of groundwater is saline and unsafe for irrigation in the study area. Particularly in saline groundwater case, leaching of salts below the root zone level through making of field bunding and ponding rain water to leach out the salts /or irrigation with mixing with good quality water (GQW) or alternate use of saline and GQW would be most useful, whereas raising green manuring crop like, Dhaincha/Sunhemp etc. (Table 4) would be added advantageous for sustain soil health and crop yield. The saline/brackish water quality can be improved if an alternate source of GQW is available. Good and saline water should be irrigated to the specific crop by 1:1 or 1:2 or 2:1 ratio by mixing and/or alternate/ cyclic mode with salt-tolerant crop varieties. Groundwater must be used judiciously (as life-saving/supplementary) only by mixing with rain water/GQW or alternately with GQW/ rain water to sustain crop yield and to avoid further deterioration in soil health. Water sodicity can be mitigated through the judicious use of calcium-containing amendments such as gypsum ($CaSO_4.2H_2O$). Relative to other amendments, gypsum is cheap and easy to handle, and by far the most suitable amendment to bring down irrigation water sodicity (the ratio of sodium to calcium + magnesium). The quantity of gypsum needed for adding to irrigation water depends upon the quality of water (RSC and SAR levels) and the quantity of water required for irrigation during the growing season of the crop. Beyond the threshold limit of sodic groundwater, medium to very high sodic level of groundwater necessitate the adoption of sodic tolerant crop varieties, with the addition of gypsum (gypsum-bed) in requisite quantity using sodic water with appropriate low-cost drainage facility in sodic soils would be beneficial for sustainable soil health as well as crop yield. In spite of the technological advances that mitigate salinity damage and the likely economic advantages, there is always a need to exercise caution while practicing irrigation with salty water for maintaining sustained productivity (Goyal and Sharma, 2015).

Conclusions

Groundwater appropriateness in an arid and semi-arid area in Jalore district, Rajasthan, has been evaluated through salinity-sodicity, residual sodium carbonate etc. criteria for irrigation use. The results show that the quality of groundwater is mainly moderately alkaline in nature. The majority of groundwater samples were high to very high salinity class (C4-C5) and high salinity with medium sodicity class (C4S2) i.e. unsafe for irrigation due to high salinity. Nearly, 15% of the groundwater samples fall in the high salinity and high sodicity hazard class (~C5S3) with continuous use of such water in the long term, which will increase both salinity and sodicity hazard in the soil. The order of the dominant cations is $Na^+ > Ca^{2+} + Mg^{2+} > K^+$ and anions are $Cl^- > SO_4^{2-} > HCO_3^- > CO_3^-$. The calculated parameters such as salinity EC, SAR, RSC, SSP, KR, PS and CR show that in all groundwater samples except a few samples, the groundwater quality is unsuitable for irrigation use. Almost 87% of groundwater was doubtful/or unsafe for irrigation due to SSP and potential salinity. While, the Kelly ratio was >1.0 in the majority (83%) of groundwater samples. In addition, 93% of groundwater samples tend to have a corrosivity ratio >1.0, which means groundwater must be transported by the PVC pipe in these areas. The corrosivity ratios indicate that a large area needs caution while transporting groundwater either for drinking or irrigation use. However, highly saline waters cannot be recommended for all the crop categories (except salt tolerant) either due to the high value of RSC or SAR. Water with high amounts of RSC may also be used, along with the required quantity of gypsum to neutralize the excess RSC. Thus, the overall results of the study indicate an alarming situation with reference to groundwater quality and it may need suitable remedial measures.

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