



Research Article

Integrated GIS-based modelling approach for irrigation water quality suitability zonation in parts of Satluj River Basin, Bist Doab region, North India



Gagandeep Singh¹ · Madhuri S. Rishi¹  · Naresh Kumar Arora²

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Abstract

The groundwater is the main source for irrigation and other purposes in the alluvial plains of Punjab. The poor irrigational water quality affects the soil quality which interrupts the growth of plants impacting the agricultural production and can cause risk to human health, and thus, it is important to evaluate the water quality for irrigation uses in the agrarian regions. An integrated GIS-based modelling approach along with conventional water quality indices such as sodium adsorption ratio, per cent sodium, residual sodium carbonate, residual sodium bicarbonate, magnesium hazard, permeability index, potential salinity, Kelly's ratio, electrical conductivity, total hardness, pH and total dissolved solids was used to delineate the irrigation water quality suitability zones in parts of agricultural prolific Satluj River Basin. Analytical results revealed that groundwater of the study area is very hard and slightly alkaline in nature and the relative abundance order of major ions is $Mg^{2+} > Na^{+} + K^{+} > Ca^{2+}$ and $HCO_3^{-} + CO_3^{2-} > Cl^{-} > SO_4^{2-}$, respectively, for cations and anions. The weighted overlay technique was applied to generate the irrigation water quality zonation map, and results revealed that nearly 3.2% (117 sq. km) of the total area was not suitable for the irrigation water quality, whereas 85.2% (3076 sq. km) and 11.6% (421 sq. km) area fall under moderately suitable and suitable classes, respectively. The elevated level of some ions found in the shallower zone as compared to the deeper zones indicates that in addition to the geogenic factors (weathering and dissolution of aquifer materials) anthropogenic inputs such as ill agricultural practices, leaching from septic tanks and municipal waste are adversely affecting the groundwater system in the region. The results of US Salinity Laboratory's diagram showed that 42% groundwater samples fall in C3S1 (high salinity with low sodium hazard) category indicating the unsuitability for irrigation purpose due to high salinity hazard and cannot be used in soils with restricted drainage. The results of Piper and Durov diagrams revealed that $Ca^{2+}-Mg^{2+}-HCO_3^{-}$ is the dominant hydrochemical facies with $Mg^{2+}-HCO_3^{-}$ water type in the groundwater of the study area and hydrochemistry is controlled by both natural and anthropogenic factors. The bottom-up approach and involvement of locals can boost the management of water resources in the study area.

Keywords GIS-based modelling · Hydrochemical facies · Irrigation water quality zonation (IWQZ) · Salinity · Sodium hazard

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✉ Madhuri S. Rishi, madhuririshi@gmail.com | ¹Department of Environment Studies, Panjab University, Chandigarh, India. ²ICAR-Central Soil Salinity Research Institute, Karnal, India.



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1 Introduction

Agriculture is a prime component of the global economy. India is an agriculture dominant nation, where 50–60% of inhabitants are directly or indirectly dependent on agriculture and allied fields that significantly contribute to the Indian economy. The agriculture sector is the main livelihood provider sector in the rural areas of India, and unquestionably, it is also the leading consumer of water resources, particularly the groundwater for the irrigational purpose [45, 46, 66]. In India, more than 90% of water withdrawal is for agricultural uses only [21]. Groundwater plays a crucial role in the socio-economic, agricultural and environmental development of a region [32, 33, 47]. Due to insufficient rainfall and surface water resources in the arid and semi-arid regions, people are mainly relying on groundwater for their needs [41]. The changes in monsoon pattern and thrust of anthropogenic activities on freshwater bodies have increased the dependence on groundwater resource in India during the last two decades [34], and due to its dynamic nature, it is easily affected by anthropogenic activities [28, 37]. The use of poor quality water for agricultural practices can be injurious to human health, crops and soils and consequently affects the crop production [4, 42, 66]. Groundwater quality deterioration has become an increasing concern globally. Several researchers have evaluated the suitability of the groundwater for irrigational uses in agriculture-rich states [6, 40, 49, 61, 63, 65, 66]. Punjab is a predominantly agrarian state of India, also known as the 'Bread Basket of the country' having 85% area under cultivation with an average cropping intensity of 188% and 72% of the total cultivated area under groundwater command (tube wells, bore wells and other sources) [44]. The state has its own success story of 'green revolution' a chemical-based agriculture model followed in India during the early 1960s. The area under investigation was the epicentre of the green revolution and made commendable progress in the production of food grains in the post-green revolution period, contributing almost one-fourth share of rice and more than one-third of wheat to the central pool of the country [39]. During that period, farmers have followed the monocropping culture of wheat and rice cycle instead of multiple cropping due to fertile alluvial plain and their surplus availability of water resource. The consumption of agrochemical fertilizers has increased significantly from 37.50 kg/ha/year in 1970 to 257 kg/ha/year during 2016 in the study area, which is also highest as compared to the national average of 165.8 kg/ha/year [23]. Furthermore, Punjab state is the third largest user of pesticides (5843 metric tonnes) after Maharashtra and Uttar Pradesh [23]. Intensive use of agrochemicals in agricultural fields is the key responsible

factor affecting the quality of the aquifers. The water-soluble chemicals dissolved in irrigated water percolate into subsurface strata, thus affecting the natural chemical equilibrium of aquifer system [45–47, 62]. Nutrients in the forms of NO_3^- , PO_4^{3-} and K^+ are common contaminants in groundwater and soils of the agricultural dominated regions. The number of groundwater abstraction units used for irrigation has been increasing at an exponential rate in the state (1.419 million in 2014–2015), and consequently, the groundwater resources in the state are also declining at an alarming rate [45, 46, 52, 62].

The Satluj River Basin (SRB) characterized as a semi-arid climatic zone is one of the most agriculturally prolific regions in the state. Agriculture is the main occupation in the region where groundwater is commonly used for agricultural activities. The high annual rate of groundwater abstraction (8600 $\text{m}^3/\text{ha}/\text{a}$), chiefly for agricultural use, has turned most of the blocks into the 'over-exploited' category in the region [52]. SRB, a part of Indus Basin, which is ranked as a most stressed aquifer in the world, is depleting at an alarming rate of 109 km^3/year [52, 55]. The present research was carried out in the East Bein sub-basin (EBSB), a part of SRB which mainly relies on groundwater for its irrigation demand. Excessive agricultural practice has put continuous pressure on the groundwater resources in this region, and therefore, potential negative impacts of agricultural activities such as salinization and sodification need to be assessed in order to prevent water and soil quality deterioration. In India, various researchers have stated groundwater pollution by nitrate due to agrarian practices, soil contamination by the indiscriminate use of agrochemicals (pesticides and fertilizers) and irrigation water quality [1, 2, 4, 33, 35, 38, 61, 65]. Uncontrolled groundwater mining, leaching of agrochemicals to the aquifers and ill agricultural practices have resulted in the pollution of the groundwater [27, 61]. It has, therefore, become crucial to evaluate the present groundwater quality scenario and its suitability for irrigational purposes for the efficient management of the groundwater resources in the region. Geographical information systems (GIS) can be a powerful technique for developing solutions for the effective management of the groundwater resources and land use planning at a local and regional scale [17, 25, 32, 56, 66]. The main objective of the present research is to delineate the groundwater suitability zones for irrigation uses in the alluvial aquifer of EBSB by integrating conventional irrigation water quality indices and GIS techniques. Instead of studying the impact of each conventional irrigation water suitability parameters individually and in isolation, an attempt has been made to integrate them in GIS environment and see the resultant impact in the area under investigation. To ascertain the validity and reliability of the final overlay, it was compared with the time tested [15, 70, 71] diagrams. The present

research will provide significant information on groundwater suitable zones for irrigation purposes in a meaningful way for the better understanding to the policymakers involved in the water resource management in India.

1.1 Study area and hydrogeology

The study area falls in the central part of Punjab state, India, and is enclosed between River Satluj and River Beas, locally known as Bist Doab region. It is located between 31°1'26.4" and 31°33'00" N latitudes and 75°3'32.4" to 76°16' 15.6" E longitudes with total geographical area of 3614 sq. km (Fig. 1). The land use land cover (LULC) of the study area is shown in Fig. 2. The study area represents semi-arid (dry to sub-moist) climatic conditions marked by hot summer and mild winter. The temperature in the study area varies between a minimum of 5 °C (in December–January) and a maximum of 45 °C (in May–June). The annual rainfall varies between 500 mm (in south-west) and 900 mm (in north-east) parts of the study area, and 65–70% of annual rainfall is received during the monsoon period from July to September [12]. The elevation of the study area varies from 164 m to 596 m above the mean sea level (Fig. 1). Geomorphologically, the study area is divided into three distinct landforms, viz. alluvial plains (AP) in the southern part, piedmont zone (PZ) in the central part and Shivalik hill range (SHR) in the northern part. Two types of alluvium, namely older alluvium (Bhangar) and newer alluvium (Khadar), are present in the EBSB. The older alluvium of Middle to Late Pleistocene age comprised of medium to fine sandy soil, silty clay, loam, sandy loam and sandy clay and

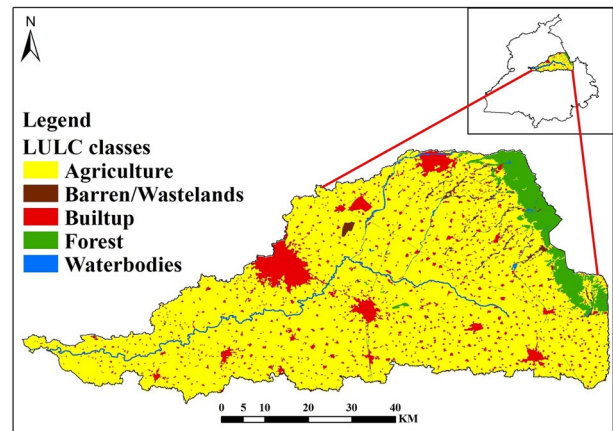


Fig. 2 LULC map of the study area

rich in calcareous material, occurs all over the district (Fig. 3 and Table 1). The newer alluvium belongs to Upper Pleistocene to Recent age, consists of coarse to medium-grained sand having a lesser amount of silt and clay and poor in the calcareous matter is restricted to the floodplains of River Satluj [11, 13, 52]. Kankar beds are more predominant in older alluvium. Sand sheets of aeolian origin of Recent age exist in the western parts of the study region. Piedmont is also classified into two types, i.e. upper PZ (also called as Kandi region) composed of coarse sediments such as cobbles, boulders, pebbles gravels and sand extends over 6–8 km and lower PZ (also called as Sirowal region) composed of fine sediments extends over 2–3 km in the central part of the study area. SHR of Late Pleistocene to Early Pleistocene age composed of friable grey micaceous sandstone, clay, shale, conglomerate and boulder beds covers the north-eastern part of the study area. Groundwater exists under both unconfined and confined conditions in these alluvial aquifers. Multiple aquifer groups consisting of fine- to coarse-grained sand are present

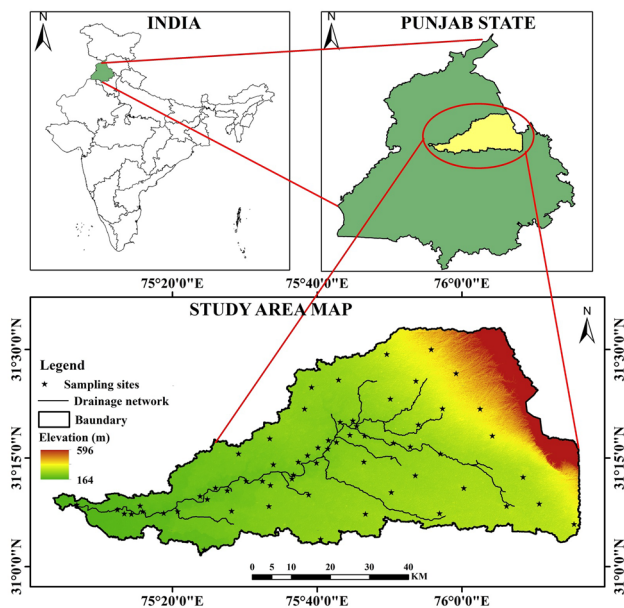


Fig. 1 Location map of the study area with groundwater sampling locations

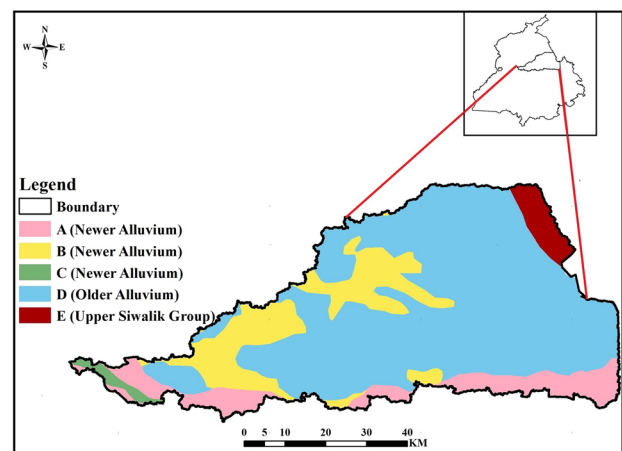


Fig. 3 Geological map of the study area

Table 1 Stratigraphic sequence of geological formations of the study area

Age	Formation	Lithology
Holocene	Newer alluvium	A Blue grey to light grey micaceous sand with alluvium interbeds of purple/red clay
		B Undifferentiated aeolian flat/sand sheet and newer dunes (N-dunes)
		C Loose grey micaceous sand along the stream courses (Recent)
Middle to Late Pleistocene	Older alluvium	D Red drift sand to loam with kankar, sticky clay (pandoo), grey medium to coarse-grained calcareous sand with kankar, sub-rounded to sub-angular unsorted pebbles, gravel and cobble beds in adjoining foothills
Late Pliocene to Early Pleistocene	Upper Siwalik group	E Friable grey micaceous sandstone, brown, red and purple clay and conglomerate

in the study area to the depth of 350 metres below ground level (m bgl). Extensive clay beds are present at the depths of 15–20, 35–40 m and 160–175 m bgl in the study region. The unconfined aquifer in the region is under tremendous stress due to the over-extraction of groundwater for irrigation and domestic purposes.

2 Materials and methods

2.1 Groundwater sample collection, analytical procedures and digitization

To meet the objective of integration of conventional irrigation suitability indices in a single overlay through GIS, a well-tested systematic random sampling technique was adopted to collect the groundwater samples from the study area. For the present research, sixty-two ($n = 62$) groundwater samples were collected using global positioning system (GPS) during the pre-monsoon season (May, 2017) from groundwater abstraction structures [(tube wells (TW), bore wells (BW)] used for agricultural and household purposes. The geographical locations of all sampling sites are shown in Fig. 1. The sample collection, transportation, conservation and analytical procedures for major ions of groundwater samples were made following the standard methods of the American Public Health Association (APHA) [7] and are given in Table 2. All the groundwater samples were collected in 1L high-density polyethylene (HDPE) bottles which were pre-washed with 10% nitric acid (HNO_3) and rinsed with double deionized water. Before sampling, the water stored in the well pipes was pumped out for 10–15 min to ensure the original composition of water. All HDPE bottles were thoroughly rinsed several times with the groundwater to be sampled to avoid unpredictable changes in characteristics as per standard protocols. Parameters like pH, electrical conductivity (EC) and total dissolved solids (TDS) were measured on-site with a portable multiparameter meter (Hanna HI98194). The accuracy of the hydrochemical data was studied by

computing the cation anion balance error (CBE) equation (Eq. 1) proposed by Domenico et al. [18], and CBE values were within the acceptable limit of $\pm 5\%$ [29].

$$\text{CBE}\% = \frac{(\sum \text{Cations}) \text{ meq/L} - (\sum \text{Anions}) \text{ meq/L}}{(\sum \text{Cations}) \text{ meq/L} + (\sum \text{Anions}) \text{ meq/L}} * 100 \quad (1)$$

The obtained analytical results were imported to the ArcMap environment in order to integrate the hydrochemical data for their spatial exploration. For the preparation of spatial distribution maps of various irrigational water quality parameters, different interpolation techniques were selected as per their data distribution and lowest mean error (ME) and root mean square error (RMSE) of the output map. Inverse distance weighted (IDW) interpolation technique was used to generate the spatial distribution maps of pH, EC, %Na and PS; simple kriging (SK) with normal score transformation was incorporated for the TH, whereas radial basis function [(RBF) (spline with tension)] and RBF (with regularized spline) were applied for TDS and MH, respectively. CARTO-DEM data were taken from the Geo-portal of Indian Space Research Organisation (ISRO) to demarcate the EBSB boundary. Hydrogeochemical characterization of the groundwater was evaluated by Piper trilinear, Durov and Schoeller diagram using Geochemist's Workbench Student Edition 12.0 software. All the calculations and statistical analysis were performed by using Microsoft Excel 2010 and Minitab 17 software. The methodology adopted for the present research is shown in Fig. 4.

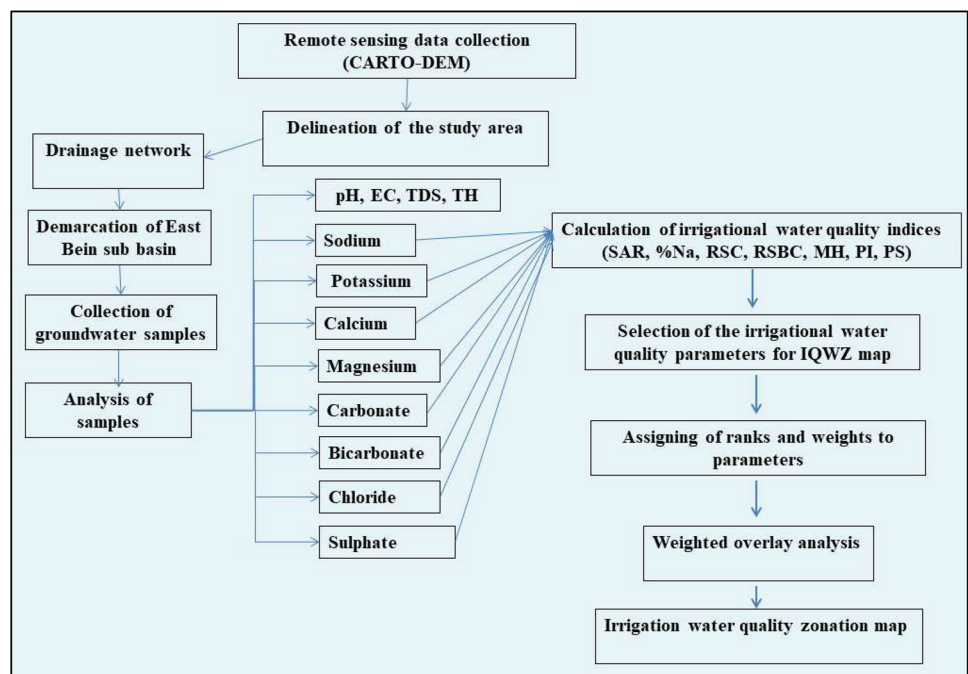
2.2 Irrigation water quality parameters

The poor irrigational water quality affects the growth of plants, agriculture production, soil quality and human health, and thus, it is important to evaluate the water quality for irrigation uses in the agrarian regions. The suitability appraisal of groundwater for irrigational purposes is determined by various irrigation water quality indices, namely sodium adsorption ratio (SAR), per cent sodium

Table 2 Statistical summary of physicochemical parameters of groundwater of the study area

Parameter	Mean ± SD	Range	Median	Analytical method
pH	8.1 ± 0.5	7.1–8.8	8.3	pH/EC/TDS meter
EC	750.1 ± 121.2	568–1060	723.2	pH/EC/TDS meter
TDS	487.5 ± 78.8	369.5–689	470.1	pH/EC/TDS meter
TH	216.6 ± 38.8	151.9–321.7	210.5	Calculation (TH = 2.5 * Ca ²⁺ + 4.1 * Mg ²⁺)
Ca ²⁺	33.3 ± 10.4	15–59.3	31.4	EDTA titration
Mg ²⁺	32.8 ± 8.4	20.4–62.3	31.9	EDTA titration
Na ⁺	43.5 ± 14.8	22.4–86.1	40.2	Flame photometric
K ⁺	11.2 ± 4.7	4.1–32.8	10.0	Flame photometric
CO ₃ ²⁻	7.4 ± 8.0	0.0–28	6.0	Titrimetric
HCO ₃ ⁻	224.1 ± 49.1	137–398	216.0	Titrimetric
Cl ⁻	46.0 ± 29.7	11.2–179	38.1	Argentometric titration
SO ₄ ²⁻	36.7 ± 23.0	4.5–123.7	30.1	Spectrophotometer

Fig. 4 Flow chart of the methodology followed to delineate the irrigation water quality suitability zonation in the study region



(%Na), residual sodium carbonate (RSC), residual sodium bicarbonate (RSBC), magnesium hazard (MH), permeability index (PI), potential salinity (PS) and Kelly’s ratio (KR), and is calculated by using the following equations (Eqs. 2–9). Further, US Salinity Laboratory’s diagram [70], Wilcox diagram [71] and Doneen’s chart [15] were also prepared to study the combined effects of EC, SAR, Na⁺ and salinity.

$$SAR = Na^+ / \sqrt{Ca^{2+} + Mg^{2+} / 2} \quad (\text{Richard 1968}) \quad (2)$$

$$\% Na = Na^+ + K^+ / Ca^{2+} + Mg^{2+} + Na^+ + K^+ \times 100 \quad (\text{Richard 1968}) \quad (3)$$

$$RSC = (CO_3^{2-} + HCO_3^-) - (Ca^{2+} + Mg^{2+}) \quad (\text{Eaton 1950}) \quad (4)$$

$$RBSC = (HCO_3^- - Ca^{2+}) \quad (\text{Gupta 1983}) \quad (5)$$

$$MH = Mg^{2+} / (Ca^{2+} + Mg^{2+}) \times 100 \quad (\text{Szabolcs and Darab 1964}) \quad (6)$$

$$PI = (Na^+ + \sqrt{HCO_3^-}) / (Ca^{2+} + Mg^{2+} + Na^+) \times 100 \quad (\text{Doneen 1964}) \quad (7)$$

$$PS = Cl^- + \sqrt{SO_4^{2-}} \quad (\text{Doneen 1961}) \quad (8)$$

$$KR = Na^+ / (Ca^{2+} + Mg^{2+}) \quad (\text{Kelly 1963}) \quad (9)$$

where all ions concentrations are expressed in meq/L.

2.3 Irrigation water quality zonation (IWQZ)

For irrigation water quality zonation mapping, a total of seven variables that are supposed to have an influence on the irrigation water quality were considered, namely pH, EC, TDS, TH, %Na, MH and PS, and they are categorized into three classes depending upon their suitability for irrigation: (1) suitable, (2) moderately suitable and (3) unsuitable classes as per the literature review [8, 15, 20, 24, 31, 36, 51, 54, 64, 66, 67, 71]. The weighted overlay analysis technique was applied to generate IWQZ map of the study area. In this technique, the following steps are involved. (1) All the input variables (in the raster form) are reclassified into the following classes as per their suitability for irrigation purposes (suitable, moderately suitable and unsuitable classes, as shown in Fig. 5). (2) Grading rank 1 was allocated to the unsuitable class, rank 2 to the moderately suitable class and rank 3 to the suitable class. (3) Since all the irrigation water quality variables are equally important in determining the irrigation water quality, equal weightage of 1 was assigned to all the input irrigational water quality variables. The assigned ranks and weights to all the variables and its subclasses are presented in Table 3. In the case of SAR, RSC, RSBC and KR, where all the groundwater samples were found within the suitable class were not considered in weighted overlay analysis. The irrigation water quality zonation map was derived by multiplying the weights and ranks of each variable followed by summing up the multiplication product of all the input rasters or variables as expressed in Eq. 10:

$$\text{IWQZ} = \sum_{i=1}^n (\text{pH}_w \times \text{pH}_r + \text{TDS}_w \times \text{TDS}_r + \text{EC}_w \times \text{EC}_r + \text{TH}_w \times \text{TH}_r + \% \text{Na}_w \times \% \text{Na}_r + \text{MH}_w \times \text{MH}_r + \text{PS}_w \times \text{PS}_r) \quad (10)$$

where w represents the weight of the factor class (each parameter), r represents the rank of the factor class, pH potential of hydrogen, TDS total dissolved solids, TH total hardness, EC electrical conductivity, $\% \text{Na}$ per cent sodium, MH magnesium hazard, PS potential salinity.

3 Results and discussion

3.1 Evaluation of groundwater for irrigational uses

Soil types, quality of water and cropping practices play an important role in sustainable irrigation practices. Salinity is an ever prevailing hazard in arid and semi-arid regions of the world and must be taken into account for the efficacious planning and management of the water resource [56]. Being an agriculturally prosperous area in the

semi-arid climatic zone, irrigation demand of the study area is mainly met by groundwater. Excess quantity of dissolved salts in the groundwater may harm the crops and soils and consequently affects the crop production [42]. Therefore, the appraisal of groundwater quality for irrigational purposes is vital for the present study. The suitability appraisal of groundwater quality for the irrigation is assessed by the following water quality indices, namely sodium absorption ratio (SAR), per cent sodium (%Na), residual sodium carbonate (RSC), residual sodium bicarbonate (RSBC), EC, TDS, Kelly's ratio (KR), magnesium ratio (MR), potential salinity (PS) and permeability index (PI) values, and their results are summarized in Table 4 and S1. In addition to this, Wilcox diagram, USSS diagrams and Doneen's chart were also prepared by incorporating the results based on various water quality indices. The statistical summary of groundwater quality parameters such as minimum, maximum, mean, median and standard deviation is given in Table 2. The relative abundance order of the major ions of the groundwater is $\text{Mg}^{2+} > \text{Na}^+ + \text{K}^+ > \text{Ca}^{2+}$ and $\text{HCO}_3^- + \text{CO}_3^{2-} > \text{Cl}^- > \text{SO}_4^{2-}$ for cations and anions, respectively (Fig. 6). pH values ranging from 7.1 to 8.8 with mean \pm standard deviation (SD) of 8.1 ± 0.49 (Table 2) indicate that the groundwater of the study area is slightly alkaline in nature. As per the classification of Ayers and Westcot [8], the desirable range of pH of 6.0–8.5 is suitable for the irrigation. The majority (85.5%) of the groundwater samples were classified in the normal range of pH (6.5–8.5) and around 14.51% groundwater samples showed pH value more than 8.5, indicating the non-suitability of groundwater for irrigation uses. Irrigation water with pH more than 8.5 can cause nutritional imbalance [10]. The TDS and TH in the study area ranged from 369.5 mg/L to 689 mg/L and 151.9 mg/L to 321.7 mg/L with mean \pm SD of 487.5 ± 78.8 and 216.6 ± 38.8 , respectively (Table 2). As per the Freeze and Cherry [22] classification of groundwater based on TDS, all the groundwater samples showed TDS value less than 1000 mg/L indicating the freshwater (Table 5). According to the Ayers and Westcot [9] and UCCC [69] classification, 40.3% samples are suitable for irrigation and the remaining 59.7% groundwater samples are moderately suitable for irrigation uses (Table 4). According to groundwater classifications by Sawyer and McCarty [57] based on TH (Table 5), 96.7% of the groundwater samples fall under hard water category and the remaining 3.23% samples fall under very hard water category indicating groundwater of the region is hard to very hard in nature. Higher value of EC affects the plant's root zone and soil fertility. The EC in the study area ranged from 568 to 1059 $\mu\text{S}/\text{cm}$ with a mean \pm SD of 750.1 ± 121.2 (Table 2). EC value more than 700 $\mu\text{S}/\text{cm}$ of irrigational water affects the flow of water and root zone [10]. According to the Richards [53] classification, 56.4% samples fall under 'good' class and the remaining 43.6% samples fall under 'doubtful' class for

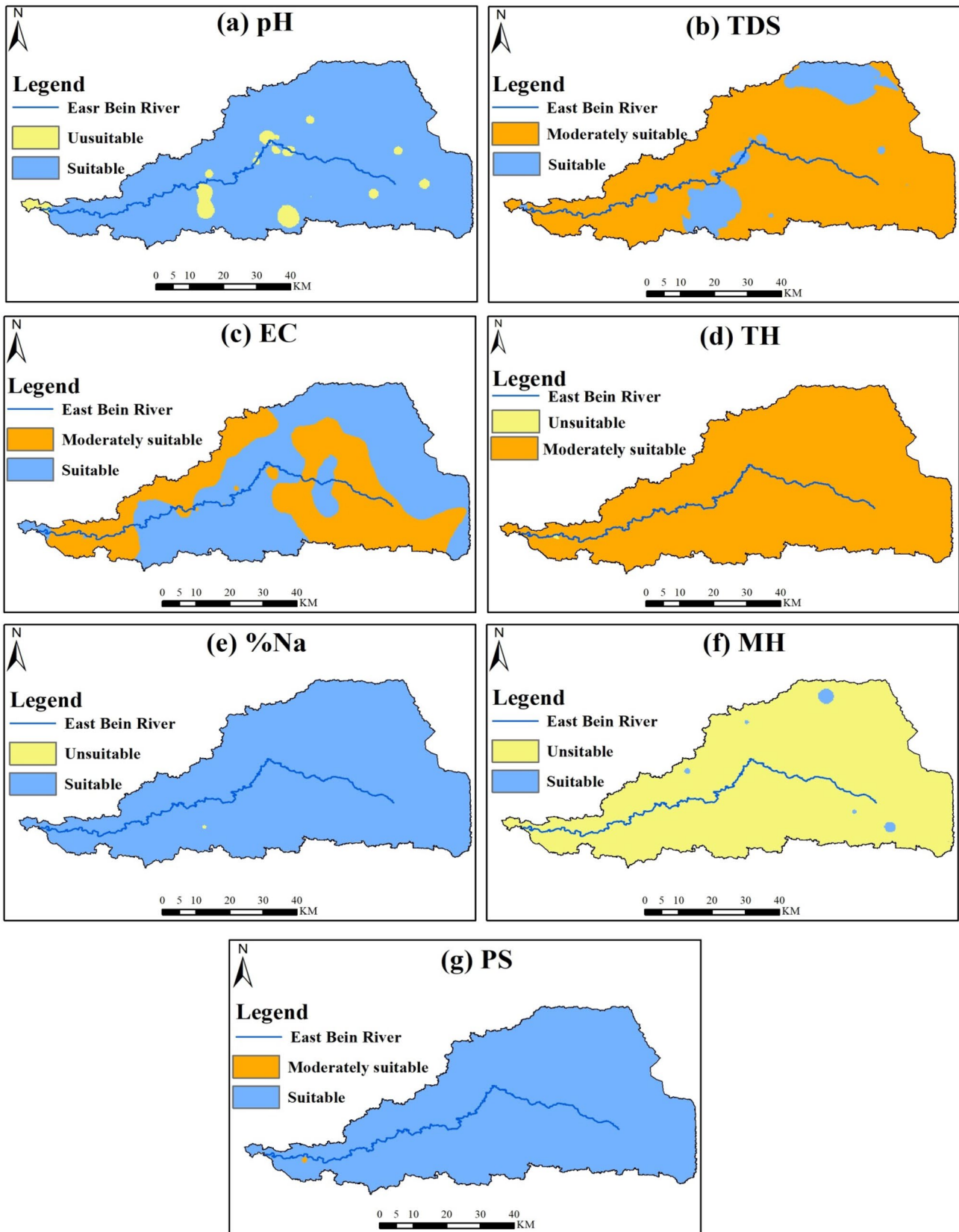


Fig. 5 Categorization of the various irrigational water quality parameters used in weighted overlay analysis: **a** pH, **b** TDS, **c** EC, **d** TH, **e** %Na, **f** MH, **g** PS

Table 3 Categorization of the various irrigational water quality parameters used in weighted overlay analysis

Parameters	Range	Water class	Rank	Weights
TDS	< 450	Suitable	3	1
	450–2000	Moderate suitable	2	
	> 2000	Unsuitable	1	
TH (as CaCO ₃ mg/L)	< 150	Suitable	3	1
	150–300	Moderate suitable	2	
	> 300	Unsuitable	1	
	> 300	Unsuitable	1	
EC (µS/cm)	< 750	Suitable	3	1
	750–2250	Moderate suitable	2	
	> 2250	Unsuitable	1	
	> 2250	Unsuitable	1	
% Na	< 50	Suitable	3	1
	> 50	Unsuitable	1	
Magnesium Hazard	< 50	Suitable	3	1
	> 50	Unsuitable	1	
pH	6.0–8.5	Suitable	3	1
	> 8.5	Unsuitable	1	
Potential salinity	< 5	Suitable	3	1
	5–10	Moderate suitable	2	
	> 10	Unsuitable	1	

irrigation. None of the groundwater samples falls in the excellent and unsuitable classes (Table 4). The ions such as Mg²⁺ and Ca²⁺ present in the water react with HCO₃⁻ to form insoluble calcium and magnesium carbonate salts, which further affects the pH and reduces the amount of Na⁺ available to plants [5].

3.2 Sodium adsorption ratio (SAR)

The sodium hazard or alkalinity hazard is usually expressed as sodium adsorption ratio (SAR) considered as a robust index for irrigation water evaluation, and it measures the relative proportion of Na⁺ ion in water to Ca²⁺ and Mg²⁺. High Na⁺ content in irrigation water alters the soil properties and also reduces the water availability to plants and soil permeability [5]. It is calculated by Eq. 2. The calculated SAR values ranged from 0.7 to 2.3 with a mean value of 1.3 (Table S1). Based on SAR classification [53], it is observed that all the groundwater samples fall into the excellent class for irrigation purposes (Table 4). It implies that the groundwater of the region is suitable for irrigation in almost all types of soils and crops.

3.3 Per cent sodium (%Na)

High Na⁺ content in water when reacting with soil reduces its permeability and destroys the soil structure due to the deflocculation process and further affects the growth of plants [8, 31, 71]. Na⁺ when combining with CO₃²⁻ forms

Table 4 Classification of groundwater of the study area based upon various irrigational indices

Parameters	Range	Water class	No. of samples	% of samples
TDS [9, 69]	< 450	Suitable	25	40.3
	450–2000	Moderate	37	59.7
	> 2000	Unsuitable	Nil	Nil
TH (as CaCO ₃ mg/L)	< 75	Soft	Nil	Nil
	75–150	Moderately hard	Nil	Nil
	150–300	Hard	60	96.7
	> 300	Very hard	2	3.3
Alkalinity hazard (SAR) [53]	< 10	Excellent (S1)	62	100
	10–18	Good (S2)	Nil	Nil
	18–26	Doubtful (S3)	Nil	Nil
	> 26	Unsuitable (S4)	Nil	Nil
Salinity hazard (EC values in µS/cm) [53]	< 250	Excellent (C1)	Nil	Nil
	250–750	Good (C2)	35	56.4
	750–2250	Doubtful (C3)	27	43.6
	> 2250	Unsuitable (C4)	Nil	Nil
% Na [71]	< 50	Suitable	60	96.7
	> 50	Unsuitable	2	3.3
RSC [20, 53]	< 1.25	Good	62	100
	1.25–2.5	Doubtful	Nil	Nil
	> 2.5	Unsuitable	Nil	Nil
RSBC [24]	< 5	Satisfactory	62	100
	5–10	Marginal	Nil	Nil
	> 10	Unsatisfactory	Nil	Nil
Magnesium Hazard (MH) [51]	< 50	Suitable	5	8.1
	> 50	Unsuitable	57	91.9
Permeability index [14]	Class I	Max. permeability	6	9.7
	Class II	75% of max. permeability	56	90.3
	Class III	25% of max. permeability	Nil	Nil
Potential salinity [14]	< 5	Excellent to good	61	98.4
	5–10	Good to injurious	1	1.6
	> 10	Injurious to unsatisfactory	Nil	Nil
Kelly's ratio (KR) [36]	< 1	Good	62	100
	1–2	Doubtful	Nil	Nil
	> 2	Unsuitable	Nil	Nil

alkaline soil and when combining with Cl⁻ leads to the formation of saline soil, and both these soils do not help in the growth of plants. The %Na is categorized into two classes, i.e. 0–50 representing the permissible class and > 50 indicating non-permissible class [67], and is calculated by using Eq. 3. The sampled water values varied from 22% to 51% with the mean value of 33% in the study area (Table S1). Table 4 shows that the majority (97%) of

Table 5 Classification of groundwater based upon TH [57] and TDS [22]

TH (as CaCO ₃ mg/L)	Water classification/type	% of samples
< 75	Soft	Nil
75–150	Moderately hard	Nil
150–300	Hard	96.77
> 300	Very hard	3.23
TDS (mg/L)	Water classification/type	% of samples
< 1000	Freshwater	100
1000–10,000	Brackish water	Nil
10,000–100,000	Saline water	Nil
> 100,000	Brine water	Nil

the groundwater samples fall in permissible class and the remaining (3%) samples belong to the non-permissible class.

3.4 Residual sodium carbonate (RSC)

RSC index also describes the alkalinity hazards of the soil. The suitability of water for irrigation purpose is also influenced by excess $\text{CO}_3^{2-} + \text{HCO}_3^-$ over the $\text{Ca}^{2+} + \text{Mg}^{2+}$ [20, 53]. High content of CO_3^{2-} and HCO_3^- than the Ca^{2+} and Mg^{2+} in the water leads to the precipitation of calcium and magnesium [60]. RSC is computed by subtracting the $\text{Ca}^{2+} + \text{Mg}^{2+}$ (alkaline earths) from the $\text{CO}_3^{2-} + \text{HCO}_3^-$ as expressed in Eq. 4. The calculated RSC value ranges from -3.06 to 1.25 (Table S1), and all the groundwater samples have RSC value less than 1.25 indicating the suitability of groundwater of the region for irrigation uses (Table 4). The negative RSC value is due to incomplete precipitation of calcium and magnesium,

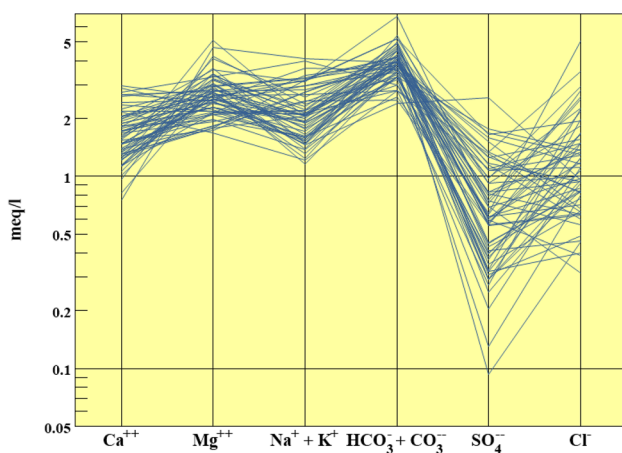


Fig. 6 Schoeller diagram representing the relative abundance of the major cations and anions of groundwater of the study area

which indicates little danger of Na^+ accumulation due to offsetting concentrations of Ca^{2+} and Mg^{2+} [3, 51], and the positive value of RSC signifies the high content of Ca^{2+} and Mg^{2+} due to the reaction of HCO_3^- to form calcium and magnesium bicarbonates [37].

3.5 Residual sodium bicarbonate (RSBC)

The surplus sodium bicarbonate and carbonate are considered to be harmful to the physical properties of soils because it increases the dissolution of organic matter in the soil [5]. RSBC is calculated by using Eq. 5 developed by Gupta [24]. All the groundwater samples are found within the satisfactory limits of RSBC (< 5 meq/L) (Table 4) suggested by Gupta [24]. The calculated RSBC value ranges from 0.23 to 4.53 meq/L with a mean value of 2.01 meq/L (Table S1), so groundwater of the region is considered safe for irrigation purpose.

3.6 Magnesium hazard (MH)

Mg^{2+} is an important ion for plants regulatory mechanism for growth [51], but its higher content in irrigation water increases the soil alkalinity and damages soil structure [16, 38] and subsequently affects the crop yields [35]. Generally, Ca^{2+} and Mg^{2+} maintain a state of equilibrium in water [38] and high Mg^{2+} content is due to the presence of exchangeable Na^+ in the irrigated soils. The MH is calculated by Eq. 6 developed by Szabolcs and Darab [64]. MH value varies from 43.7 to 86.3 meq/L with mean value of 61.7 meq/L (Table S1). As per Szabolcs and Darab [64] and Rangunath [51], the majority of groundwater samples (about 92%) of the study area were not suitable for irrigation as MH ratio is more than 50 meq/L and the remaining 8% samples are suitable for irrigation use (Table 4). High content of Mg^{2+} can be attributed to dissolution of dolomite in the alluvial aquifer system of the region.

3.7 Permeability index (PI)

The high content of Na^+ , Ca^{2+} , Mg^{2+} and HCO_3^- ions strongly influences the soil permeability, which in turn influences irrigation water quality [30, 66]. Due to the low permeability of the soil, water availability to the crops is reduced which affects the cropping process through crusting of seedbeds, salinity and various nutritional problems [50]. Doneen [15] developed a criterion to evaluate irrigation water suitability based on the permeability index as expressed in Eq. 7, accordingly, water is classified as Class I, Class II or Class III. In the present investigation, the PI value varies between 21.9 and 39.5% with mean value of 32.9% (Table S1). A perusal of Doneen's chart (Fig. 7) shows that 9.7% of groundwater samples fall in Class I category, i.e.

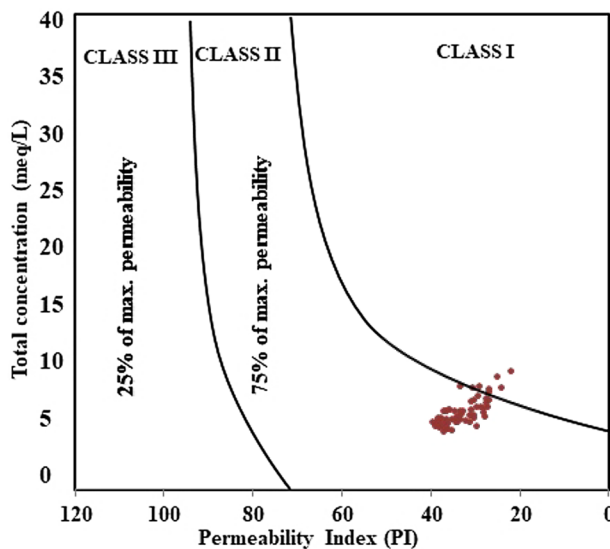


Fig. 7 Doneen [15] irrigation water classification diagram based on permeability index (PI)

100% permeability of the soil, and the remaining 91.3% groundwater samples fall in Class II, categorized as good for irrigation with 75% of maximum permeability (Table 4). None of the groundwater samples fall in Class III.

3.8 Potential salinity (PS)

In each successive irrigation, the low soluble salts are accumulated in the soil and increase its salinity [50]. Doneen [14] developed the index 'potential salinity' to determine the quality of water on the basis of salinity and is expressed as the concentration of Cl^- ions plus half of the SO_4^{2-} ions. Equation 8 was used to calculate the PS. The PS value varies from 0.85 to 5.85 with a mean value of 2.13 (Table S1). As per the Doneen's classification, the majority (98.4%) of the groundwater samples fall under the 'excellent to good' class and the remaining 1.6% samples fall in 'good to injurious' class (Table 4).

3.9 Kelly's ratio (KR)

KR is one of the important parameters for the irrigation water quality evaluation, and it measures Na^+ ion against Ca^{2+} and Mg^{2+} ions. Kelly's ratio is developed by Kelly [36], and Eq. 9 was used for the computation of KR. KR more than one implies excessive Na^+ content, whereas KR less than one indicates Na^+ deficit and is considered to be good for irrigation [36]. KR ranges from 0.23 to 0.92 with a mean value of 0.45 (Table S1) in the study area. In all the sampling locations, KR is less than 1 indicating the suitability of groundwater for the irrigation (Table 4).

3.10 Graphical interpretation of USSL diagram and Wilcox diagram

The US Salinity Laboratory's diagram [70] is also used for the suitability appraisal of irrigation water quality, which expresses the sodium hazard with respect to salinity hazard. The SAR versus EC values of groundwater samples were plotted in the USSL diagram (Fig. 8); this illustrates that majority of the groundwater samples (58%) fall in the field C2S1 (medium salinity with low sodium hazard) indicating that groundwater of the region was good for irrigation to all the crops and soils without any special consideration of salinity control. The remaining 42% groundwater samples fall under C3S1 (high salinity with low sodium hazard) category indicating that groundwater was not appropriate for irrigation purpose due to high salinity hazard and cannot be used in soils with restricted drainage [38, 63]. High content of salts in irrigation water may alter the osmotic pressure in the root zone and cause nutritional disorder and consequently affects crop growth [51].

Wilcox diagram [71] is an important graphical technique extensively used to understand the combined effect of EC and %Na for the irrigation water quality assessment. Figure 9 depicts that 56.45% groundwater samples fall in 'excellent to good' class, and the rest of 43.55% samples are under 'good to permissible' class for irrigational purposes. None of the groundwater samples falls in 'permissible to doubtful', 'doubtful to unsuitable' and 'unsuitable' classes. The results of the Wilcox diagram clearly demonstrate that the groundwater of the study area was suitable for irrigation. There are several problems associated with the low rate of infiltration such as soil crusting, lack of aeration, crusting of seed beds and inadequate nutrient availability which further affect the cropping system [21]. Figure 10 (SAR versus salinity plot) illustrates the relationship between salinity and sodicity and infiltration rate of groundwater. A perusal of Fig. 10 shows that all the groundwater samples fall in 'no reduction in rate of infiltration zone' and 'slight to moderate reduction in rate of infiltration zone' indicating the suitability of the groundwater of the region for irrigation (Fig. 10).

3.11 Irrigation water quality zonation (IWQZ)

A composite irrigation water quality zonation map of the study area is presented in Fig. 11 which clearly portrays that major portion [85.2% (3076 sq. km)] of the studied region was under moderately suitable irrigation water quality zone, whereas 11.6% (421 sq. km) and 3.2% (177 sq. km) of the total area fall under suitable and unsuitable irrigation water quality zones, respectively. The groundwater

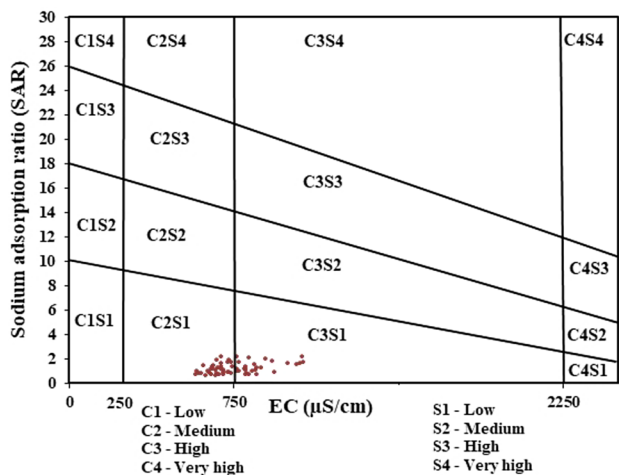


Fig. 8 USSL diagram indicating the suitability of groundwater for irrigation

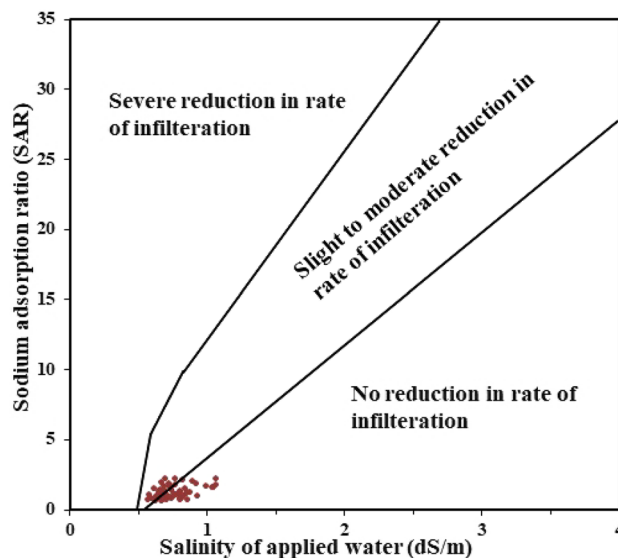


Fig. 10 SAR versus salinity diagram of the groundwater samples of the study area

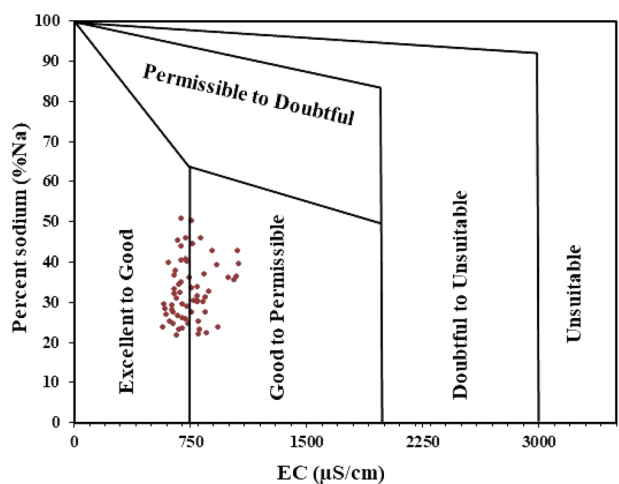


Fig. 9 Wilcox diagram indicating the suitability of groundwater for irrigation

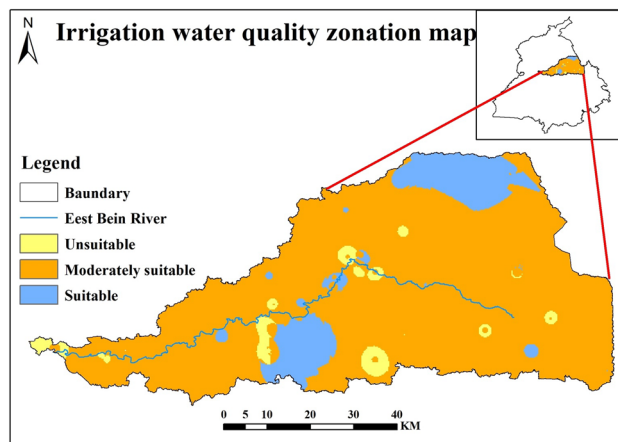


Fig. 11 Composite irrigation water quality zonation map of the study area

that is considered to be suitable for crop irrigation spreads all over the study area, but mostly remains confined to the northern and south-western parts. Unsuitable irrigation water quality zones are conspicuous in small patches throughout the study area (Fig. 11). Vertical variation of water quality variables was also studied at different depths. Almost all the water quality parameters show a decrease in concentration with the changing depth of well (Fig. 12). The wide variation in the chemical nature of groundwater was observed in the shallow zone up to the depth of 50 m below ground level (m bgl). The maximum concentration of Ca^{2+} , Mg^{2+} , Na^+ , K^+ and Cl^- was recorded between 40 and 50 m bgl, whereas the maximum concentration of HCO_3^- , CO_3^{2-} and SO_4^{2-} was recorded between 60 and 75 m bgl (Fig. 12). Groundwater quality

in the shallower zone is more contaminated with the ions as compared to the deeper zones; this indicates that in addition to the geogenic factors (weathering and dissolution of aquifer materials) anthropogenic inputs such as ill agricultural practices, leaching from septic tanks and municipal waste significantly deteriorate the groundwater system in the region. Moreover, the study region lacks well-developed sewerage or drainage system and wastewater is directly discharged into nearby streams and rivers are another key responsible factor for the deterioration of shallow groundwater quality. Disposal of untreated domestic and industrial effluents and indiscriminate use of agrochemicals have rendered the groundwater unfit for irrigation purposes. Overall, groundwater of the region is

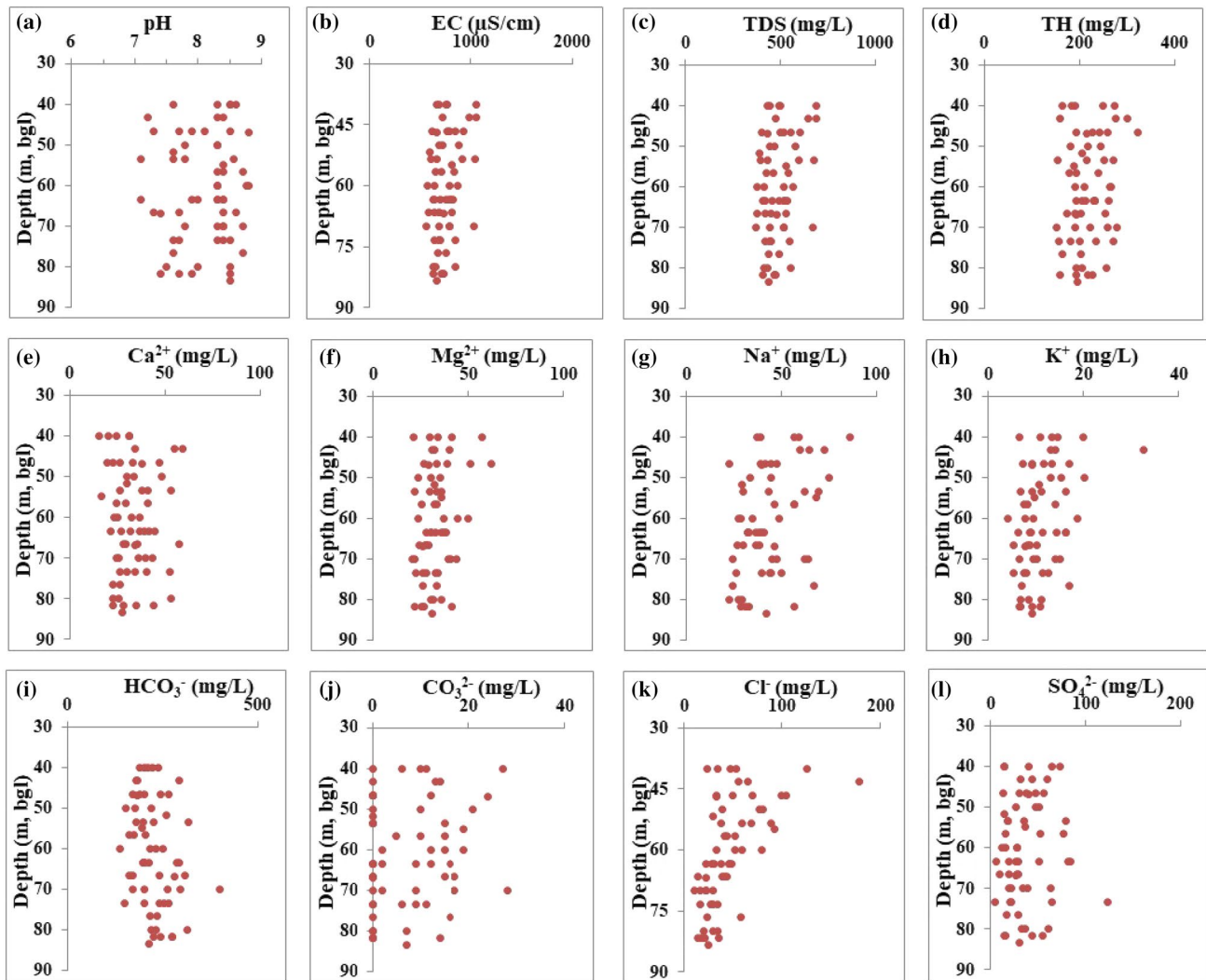


Fig. 12 Vertical trends of water quality parameters: **a** pH, **b** EC, **c** TDS, **d** TH, **e** Ca^{2+} , **f** Mg^{2+} , **g** Na^+ , **h** K^+ , **i** HCO_3^- , **j** CO_3^{2-} , **k** Cl^- and **l** SO_4^{2-}

unsuitable for long-term irrigation, considering the high magnesium and sodium hazard and salinity in the water [26]. High Na^+ content in the irrigational water can replace Ca^{2+} and Mg^{2+} ions in the soil, which further makes the soil compact by reducing its permeability [10]. High salinity also affects soil structure through flocculation/deflocculation processes. Continuous irrigation with saline waters also increases the soil salinity and affects the crop yield.

3.12 Hydrochemical characterization of the groundwater

Hydrogeochemical characterization and geological information are utmost important for the efficient management of the water resources in the aquifer [33, 47]. The water quality chemical data were plotted on the Piper trilinear diagram [48] in order to understand the

hydrochemical facies and associated processes in the groundwater of the area under investigation. Geochemist's Workbench Student Edition 12.0 software was used for plotting the Piper diagram. Table 6 and Fig. 13 reveal that $\text{Ca}^{2+}\text{-Mg}^{2+}\text{-HCO}_3^-$ (90.3%) hydrochemical facies is the predominant facies followed by $\text{Ca}^{2+}\text{-Mg}^{2+}\text{-Cl}^- \text{-SO}_4^{2-}$ (8.1%) and $\text{Na}^+\text{-K}^+\text{-HCO}_3^-$ (1.6%). It indicates that both natural process (mineral dissolution, interactions of aquifer materials) and anthropogenic activities such as irrigation return flow, septic tank effluents and municipal wastewater were influencing the hydrochemistry of the region [34, 59]. It is clearly evident from the Piper diagram that the alkaline earths ($\text{Ca}^{2+}\text{-Mg}^{2+}$) significantly exceed the alkalis ($\text{Na}^+\text{-K}^+$) and weak acids ($\text{HCO}_3^- \text{-CO}_3^{2-}$) exceed over the strong acids ($\text{Cl}^- \text{-SO}_4^{2-} \text{-F}^-$) in the study region (Table 6 and Fig. 13). About 90.3% groundwater samples that had carbonate hardness (secondary alkalinity) exceed 50%,

Table 6 Hydrochemical facies of the groundwater of the study area derived from Piper diagram

Class	Groundwater types corresponding to subdivisions of facies	No. of samples	% of samples
I	$\text{Ca}^{2+}\text{-Mg}^{2+}\text{-Cl}^{-}\text{-SO}_4^{2-}$	5	8.1
II	$\text{Na}^{+}\text{-K}^{+}\text{-Cl}^{-}\text{-SO}_4^{2-}$	Nil	Nil
III	$\text{Na}^{+}\text{-K}^{+}\text{-HCO}_3^{-}$	1	1.6
IV	$\text{Ca}^{2+}\text{-Mg}^{2+}\text{-HCO}_3^{-}$	56	90.3
1	Alkaline earths ($\text{Ca}^{2+}\text{-Mg}^{2+}$) exceed alkalies ($\text{Na}^{+}\text{-K}^{+}$)	61	98.4
2	Alkalies exceed alkaline earths	1	1.6
3	Weak acids ($\text{HCO}_3^{-}\text{-CO}_3^{2-}$) exceed strong acids ($\text{Cl}^{-}\text{-SO}_4^{2-}\text{-F}^{-}$)	57	91.9
4	Strong acids exceed weak acids	5	8.1
5	$\text{Ca}^{2+}\text{-Mg}^{2+}$ and $\text{HCO}_3^{-}\text{-CO}_3^{2-}$ (temporary hardness); magnesium bicarbonate type (carbonate hardness (secondary alkalinity) exceeds 50%)	56	90.3
6	$\text{Ca}^{2+}\text{-Mg}^{2+}$ and $\text{Cl}^{-}\text{-SO}_4^{2-}$ (permanent hardness); calcium chloride type (non-carbonate hardness (secondary salinity) exceeds 50%)	5	8.1
7	$\text{Cl}^{-}\text{-SO}_4^{2-}$ and $\text{Na}^{+}\text{-K}^{+}$ (saline); sodium chloride type (non-carbonate alkali (primary salinity) exceeds 50%)	Nil	Nil
8	$\text{HCO}_3^{-}\text{-CO}_3^{2-}$ and $\text{Na}^{+}\text{-K}^{+}$ (alkali carbonate); sodium bicarbonate type (carbonate alkali (primary alkalinity) exceeds 50%)	1	1.6
9	None of the cation and anion pairs exceed 50%	6	9.7
A	Calcium type	Nil	Nil
B	No dominant (cations)	49	79.0
C	Magnesium type	11	17.7
D	Sodium type	2	3.2
E	Bicarbonate type	58	93.5
B	No dominant (anions)	3	4.8
F	Sulphate type	Nil	Nil
G	Chloride type	1	1.6

as indicated by temporary hardness, it may be due to the weathering of the silicates in the study area [27], whereas 8.1% samples showed permanent hardness and secondary salinity (non-carbonate hardness), thus supporting the results of IWQZ. Among cations, 79% samples fall in no dominance zone of the cation triangle and 17.7% samples showed Mg^{2+} type of water. As far as anion triangle is concerned, the majority (93.5%) of groundwater samples were bicarbonate-type water followed by chloride type clearly indicating hard nature of groundwater in the region and 4.8% samples fall under no dominance zone (Table 6 and Fig. 13). In addition to Piper trilinear diagrams, Durov diagram was also used to delineate the hydrogeochemical facies and possible geochemical processes (mixing, cation exchange, reverse ion exchange dissolution) influencing the groundwater of the region (Fig. 14). As per the Lloyd and Heathcote [43] classification, 71% groundwater samples fall under sixth field indicating dominance of Mg^{2+} and HCO_3^{-} in the groundwater system (Fig. 14), demonstrating the water type that is not frequently encountered; this could be due to the partial ion exchange processes involved in the alluvial aquifers. About 29% groundwater samples are attributed to the mixed zone with no

dominance of major anions or cations indicating dissolution or mixing influence in the aquifer system of the study area. Hence, it is evident from the Piper and Durov diagrams that both natural geochemical and anthropogenic factors are regulating the hydrogeochemistry of the region (Figs. 13, 14).

4 Conclusion

Agriculture and allied fields are the backbone of the Indian as well as Punjab economy. The area under investigation is agriculturally productive and also facing negative impacts of excessive agricultural processes due to the overdraft of groundwater, quality deterioration and salinity in some parts of the region. This study provides significant information on groundwater quality for irrigational use in the East Bein sub-basin, Northeast Punjab, in a meaningful way for the better understanding to the policymakers involved in the water resource management in India. For the present study, conventional water quality indices such as SAR, %Na, RSC, RSBC, MH, PI, PS, KR, EC, TH, pH and TDS under GIS environment were applied to demarcate

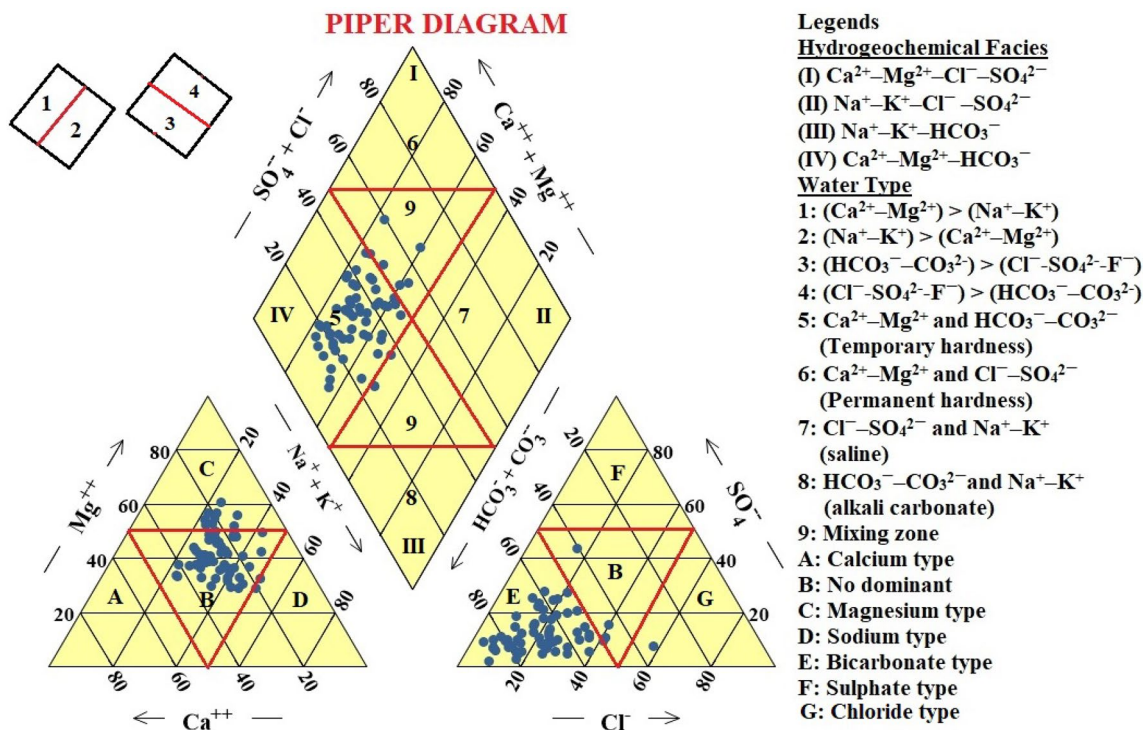
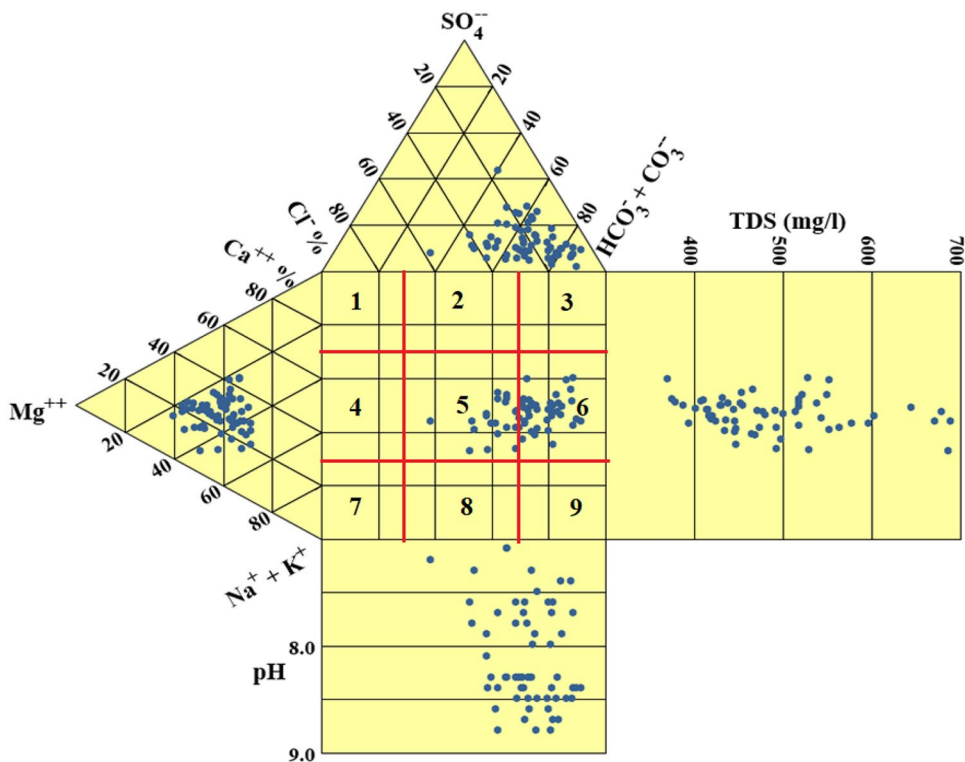


Fig. 13 Piper diagram representing hydrogeochemical facies of groundwater of the study area

Fig. 14 Durov diagram showing the hydrochemical facies involved in the study area. (1) Cl^{-} and Ca^{2+} dominant. (2) SO_4^{2-} dominant or anions indiscriminate and Ca^{2+} dominant. (3) HCO_3^{-} and Ca^{2+} dominant. (4) Cl^{-} dominant and no dominant cation. (5) No dominant anions or cations. (6) HCO_3^{-} and Mg^{2+} dominant. (7) Cl^{-} and Na^{+} dominant. (8) SO_4^{2-} dominant or anions indiscriminate and Na^{+} dominant. (9) HCO_3^{-} and Na^{+} dominant



the potential suitable zones for the irrigational purposes. Before being subjected to the weighted overlay analysis, different interpolation techniques were applied to generate spatial distribution maps of various irrigational water parameters on the basis of data distribution and lowest mean error (ME) and root mean square error (RMSE). The results of the composite IWQZ map revealed that around 3.2% (117 sq. km) of the total area was found inappropriate for the irrigation water quality, whereas 85.2% (3076 sq. km) and 11.6% (421 sq. km) area fall under moderately suitable and suitable class irrigation water quality zones. The major portion of the studied region is under moderately suitable irrigation water quality zone, and some patches with unsuitable irrigation water quality zones are also conspicuous throughout the study area. The analytical results revealed that groundwater in the study area is slightly alkaline and very hard in nature. The elevated level of some ions found in the shallower zone as compared to the deeper zones signifies that in addition to the geogenic factors (weathering and dissolution of aquifer materials) anthropogenic inputs such as ill agricultural practices, leaching from septic tanks and municipal waste are adversely affecting the groundwater quality in the region. The results of hydrogeochemical evaluation indicated that $\text{Ca}^{2+}\text{-Mg}^{2+}\text{-HCO}_3^-$ is the predominant hydrochemical water facies with $\text{Mg}^{2+}\text{-HCO}_3^-$ water type indicating temporary hardness with secondary salinity in the region. The USSS, Wilcox and Doneen diagrams indicated low to high salinity in the region, and thus, the study signifies that the area under investigation demands attention for the efficient management of the water resources. The unsuitable region for the irrigation in the study area may extend further; thus, stringent norms for the management of the groundwater quality are required.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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