Spatial interpolation approach-based appraisal of groundwater quality of arid regions

Kanak Moharir, Chaitanya Pande, Sudhir Kumar Singh, Pandurang Choudhari, Rawat Kishan and Lordwin Jeyakumar

ABSTRACT

The primary objective was appraisal of groundwater quality during pre- and post-monsoon seasons for irrigation purposes. Good quality groundwater is required for high crop yields in arid regions. A total of 45 samples were collected from wells and analyzed in the laboratory for this research work. Different water quality parameters were determined from these samples, namely electrical conductivity (EC), sodium adsorption ratio (SAR), residual sodium carbonate (RSC), sodium percent (Na%), and permeability index (PI) during the pre- and post-monsoon season. The water types were identified through a Piper-trilinear diagram. Fifty per cent of the water samples of the total basin area fall under the saline category. The local farmers heavily rely on groundwater for the irrigation of crops. Excess use of groundwater for irrigation raises soil salinity. Some parts of the study area are facing serious problems such as loss of crop yields, and low availability of good quality groundwater even for drinking purposes. The results highlight that the study area has a high salinity content (C3) and low sodium (S1). The maps for different water quality parameters were generated using inverse distance weighted (IDW) interpolation method in ArcGIS 10.3 software.

Key words | arid region (AR), inverse distance weighted (IDW), permeability index (PI), Piper diagram, residual sodium carbonate (RSC), sodium absorption ratio (SAR)

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INTRODUCTION

Groundwater is an important water resource for human development (Singh *et al.* 2009, 2010; Murmu *et al.* 2019; Pande *et al.* 2019). Generally, water supplies from groundwater are permitted due to natural purification through soils and sediments (Karanth 1987; Stigtera *et al.* 1998; Guo & Wang 2004; Rajmohan & Elango 2004, 2006; Khadri & Pande 2016; Moharir *et al.* 2017). Due to rapid industrialization and increasing human population, the stress on groundwater is continuously rising, and conservation is one of the foremost challenges for humanity (Gajbhiye *et al.* 2015; Kumar *et al.* 2018; Thakur *et al.* 2013, 2015; Srivastava *et al.* 2013; Singh *et al.* 2018a, 2018b). The study of hydro-geochemistry helps in understanding the quality of water for different purposes (Gautam *et al.* 2015, 2016, 2018; Jacintha *et al.* 2016; Kumar *et al.* 2015). Both agricultural and anthropogenic activities have resulted in a reduction of water quality posing a serious threat to humans and animals (Kaur *et al.* 2016; Nemčić-Jurec *et al.* 2019; Rawat *et al.* 2018a, 2018b, 2018c, 2019). Human health may also be affected due to contamination of toxic elements and micro-organisms present in the drinking or irrigation water (Yang *et al.* 2002; WHO 2004; USEPA 2006;

doi: 10.2166/aqua.2019.026

De Figueiredo et al. 2007; Nemčić-Jurec et al. 2019). In coastal areas, salt water intrusion is a serious problem (Voudouris et al. 2004; Mimikou 2005; Daskalaki & Voudouris 2008; Sofios et al. 2008; Rawat et al. 2018d, 2018e; Saravanan et al. 2018a, 2018b). The hydro-geochemistry configuration of groundwater is controlled by hydrogeology, rock types, geochemical minerals, and anthropogenic activities, soils and crops, precipitation, geological structure (Murray 1996; Rosen & Jones 1998; Nishanthiny et al. 2010). In countries like India, around 80–90% of diseases have been directly related to the quality of unsafe drinking water (Prasad 1998; Olajire & Imeokparia 2001; Essumang et al. 2011; Khadri et al. 2013; Pazand & Hezarkhani 2013).

Soil salinization is a serious threat to agriculturalists and groundwater managers (Edmunds et al. 2003). The adoption of control measures must be cost-effective (Mull et al. 1992). The irrigation indices sodium adsorption ratio (SAR), Na%, residual sodium carbonate (RSC), and PI are widely used to evaluate groundwater quality for irrigation purpose (Al-Bassam & Al-Rumikhani 2003; Gallardo & Tase 2007; Singh et al. 2015; Nemčić-Jurec et al. 2019). In arid areas, the groundwater quality for irrigation purposes needs to be evaluated to understand the soil salinization. The objective was to evaluate the suitability of groundwater for agricultural use through irrigation indices and apply spatial interpolation technique to develop thematic maps the arid region of Maharashtra, India. The results can be useful to in the agriculture sector.

MATERIALS AND METHODS

Study area

The study area lies in the Akola and Buldhana districts of Maharashtra, India. The study area is covered by basaltic rock. A survey of India's topographical sheets numbers 5D/7, 55D/9, 55D/11, 55D/13, 55D/14, and 55D/15 on a scale of 1:50,000 was used for preparation of the base map of the study area (Figure 1(a) and 1(b)). The main economic activity is agriculture and farmers are growing crops such as cotton, pigeon-pea, soybean, etc. In this catchment, the soil is melanocratic (black cotton soil) due to its basaltic composition. The average annual rainfall in the catchment ranges between 750 and 850 mm. The topography is undulating and interspersed in the arid area and covers a large number of alluvial patches.

Sample collection

The location map was prepared using ArcGIS 10.3 software with the reference of topographical sheets and field data. The groundwater samples were collected during the pre- and post-monsoon season. Samples were collected from 45 wells located across the study area. The sampling observational wells locations were fixed using a Global Positioning System (GPS). The groundwater samples were collected after 10 minutes of pumping and stored in 1 L plastic bottles which had previously been soaked in 10% nitric acid (HNO_3) for 24 hours and rinsed with de-ionized water. The groundwater samples were investigated in triplicate for their hydro-chemical elements under standard techniques for the investigation of groundwater quality parameters established by the American Public Health Association (APHA 1998). The samples were filtered with 0.45 µm Millipore membrane filters. The pH and electrical conductivity (EC) was determined in the field using a pH and EC digital probe.

Laboratory analysis and irrigation indices

Acid titration and moly-do silicate techniques have been used for determining the concentration of bicarbonate and dissolved silica, correspondingly (APHA 1998). An overall accuracy explained as the percent relative standard deviation (RSD) was attained below 10% for every water sample in the observation wells. The irrigation indices SAR, sodium percentage, and PI respectively were also calculated.

Water facies

The study of hydro-geochemical facies is a useful method in determining the water flow pattern and the origin of hydro-chemical data histories of groundwater. It is used to identify direct relationships and dissimilarities related to chemistry of groundwater samples based on the leading cations and anions (Piper 1953). It suggests groundwater changes have been related to geochemical issues in the arid area. The Piper diagram consists of three distinct

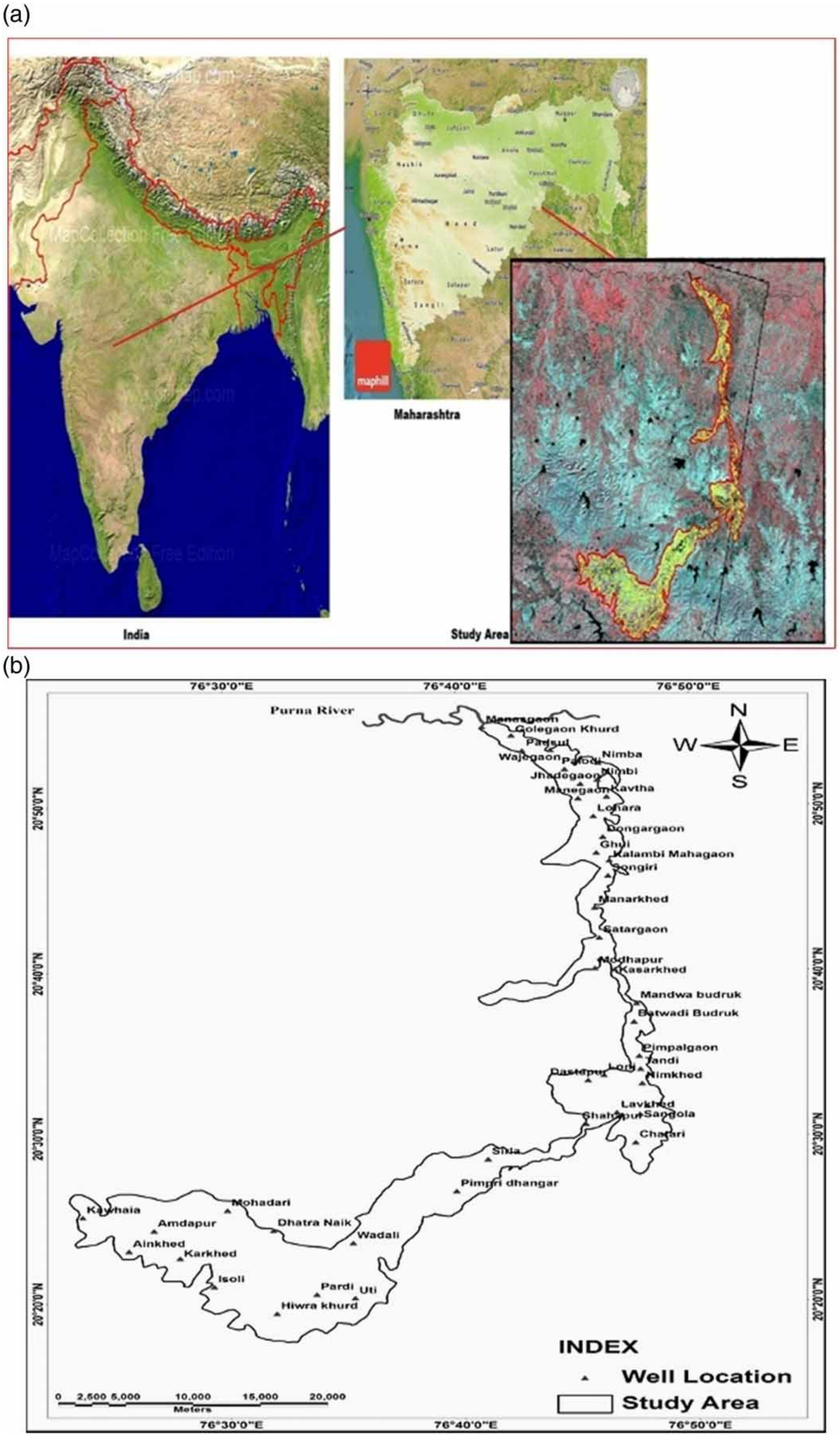

Figure 1 | Study area map: (a) location of study area, (b) sample of open/bore wells map during pre-/post-monsoon.

fields, two triangular fields and a point (dotted) field. Percentage equivalents per mole values were used for plotting groundwater quality parameters (Todd 1980). Groundwater parameters ranges were distinguished with their plotting locations occupied by the location point during the pre- and post-monsoon season.

Spatial interpolation technique

The inverse distance weightage (IDW) interpolation method was adopted. The IDW method has been most commonly used by many researchers due to its robust nature (Gong et al. 2014; Elumalai et al. 2017; Singh et al. 2013a, 2013b). Groundwater quality values were measured by surrounding an unmeasured site that has been utilized for the forecast of pre-/post-monsoon water quality values in the arid region. Predictions by this deterministic method are based on a linear combination of nearly situated values. Shepard (1968) defines IDW by Equations (1) and (2):

$$Z = \frac{\sum_{i=1}^{n} W_i Z_i}{\sum_{I=1}^{n} W_i} \quad (1)$$

$$W = \frac{1}{d_i^p} \quad (2)$$

where z is the interpolated value, z_i is the known value, n is the total number of known values used in interpolation, d_i is the distance between known and interpolated values, and p is the power parameter where weight decreases as distance increases from the interpolated values.

RESULTS AND DISCUSSION

Hydro-geochemistry

The pH value of the samples vary from 6.1–9.2 and 6.3–9.5 during pre- and post-monsoon in the arid region which indicates that the groundwater of the study area is acidic to alkaline. The minimum, maximum, mean and standard deviation values of all the parameters are given in Table 1. The Ca–HCO_3, Na–Cl, mixed Ca–Na–HCO_3 and mixed Ca–Mg–Cl types of groundwater were dominant in this region as indicated in Figure 2.

Water quality parameters have been determined for the irrigation suitability of the wells. Table 1 shows the descriptive statistics of irrigation indices of pre- and post-monsoon seasons. Table 2 shows the irrigation parameters (EC, SAR, RSC, Na%, and PI) values of pre- and post-monsoon seasons at sampling locations. Table 3 shows the classification of

Table 1 | Statistical analysis for pre-/post-monsoon summary of various parameters in groundwater ($N = 45$)

Sr. no.	Pre-monsoon				Post-monsoon			
Parameters	Minimum	Maximum	Mean	Standard deviation	Minimum	Maximum	Mean	Standard deviation
pH	6.1	9.2	7.06	0.80	6.3	9.5	7.16	0.766
TDS	234.77	810.22	452.87	103.80	297.93	822.5	476.39	14.64
Ca	2	7.09	4.24	1.25	2	7.78	4.26	1.16
CO_3	0	0.43	0.19	0.15	0	0.79	0.33	0.26
HCO_3	1.03	9.57	4.01	2.34	1.07	11.16	5.73	2.94
Mg	1.9	9.12	4.73	1.67	2.07	10.21	5.20	1.65
Cl	0.34	23.84	10.38	6.55	0	23.06	8.60	5.67
SO_4	0.48	4.64	2.92	1.22	0.85	5.37	3.17	1.31
EC μs/cm	312	1500	781.82	266.64	312	1598	195.28	281.39
SAR meq/L	0.26	5.02	1.19	0.96	0.18	85	3.91	13.79
RSC meq/L	−14	2.92	−4.71	3.32	−14	2.92	−6.10	4.03
Na%	7.7	64.4	25.81	13.25	7.7	64.4	24.18	13.62
PI	12.66	63.2	30.32	11.33	12.66	63.2	32.46	11.91

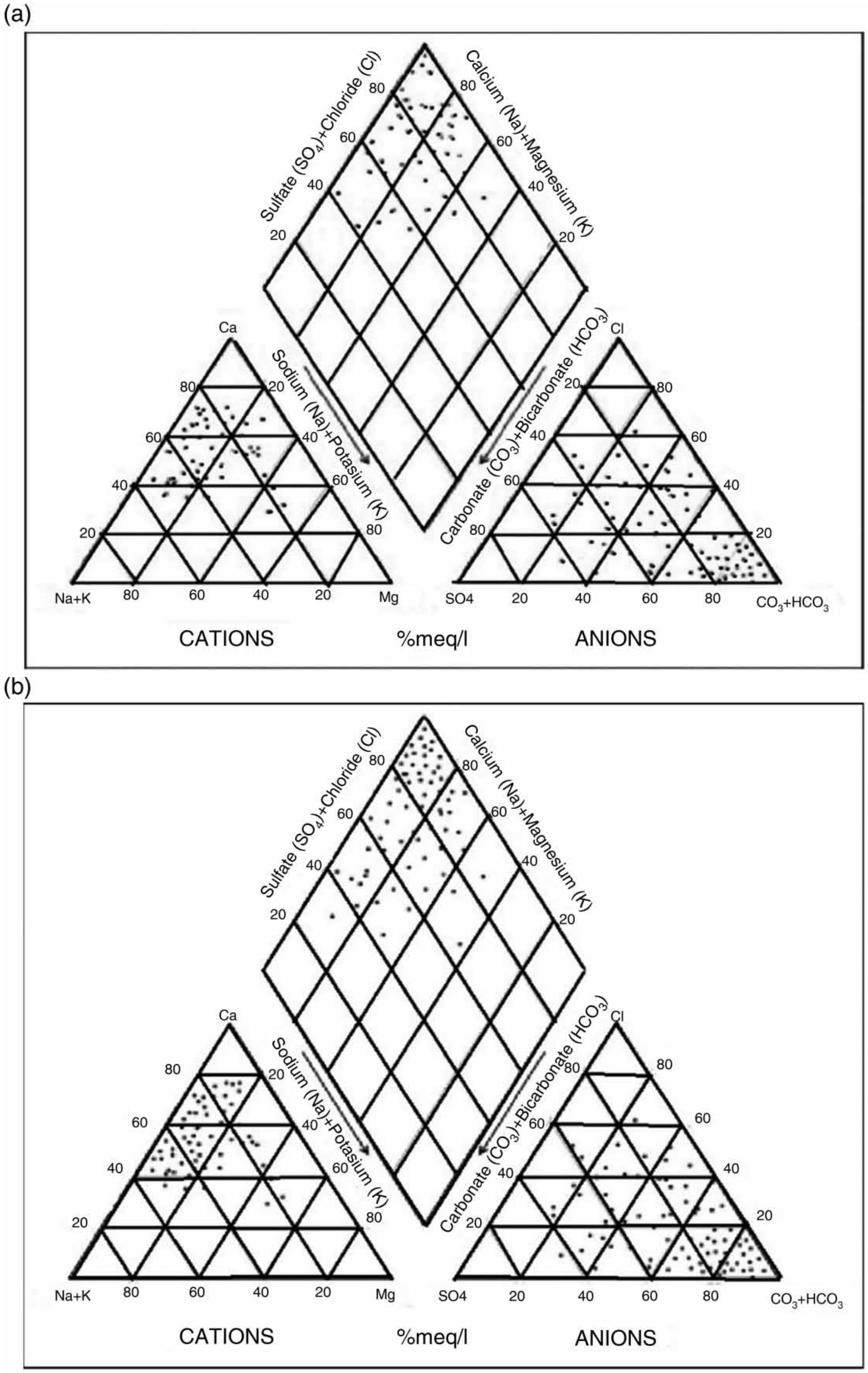

Figure 2 | Piper-trilinear diagram of the (a) pre-monsoon and (b) post-monsoon seasons.

Table 2 | Parameters of irrigation groundwater quality in pre-/post-monsoon

		Pre-monsoon					Post-monsoon				
Sample no.	**Village name**	**EC μs/cm**	**SAR meq/L**	**RSC meq/L**	**Na%**	**PI**	**EC μs/cm**	**SAR meq/L**	**RSC meq/L**	**Na%**	**PI**
1	Hingaonnimba	987	0.33	−6.56	15.2	19.14	908	0.68	−8.39	21.62	32.63
2	Wajegaon	1414	1	−1.56	36.8	28.97	1598	0.9	−10.56	23.38	32.17
3	Nimba	987	0.73	−3.41	19.2	25.63	1005	0.58	−10.04	17.88	38.47
4	Kavtha	823	1.74	−5.58	31	36.92	934	0.61	−10.39	17.56	34.58
5	Lohara	902	0.98	−6.67	29.8	29.86	935	0.21	−8.05	18.14	23.25
6	Dongargaon	902	1.02	−5.28	24.6	32.28	985	0.99	−8.14	27.46	50.75
7	Songiri	905	1.62	−5.88	30.4	36.4	935	0.88	−12.42	21.73	34.27
8	KalambiMahagaon	824	1.45	−7.3	26.9	32.41	856	0.59	−11.08	16.64	26.91
9	Manarkhed	913	0.84	−7.68	18.9	24.75	968	0.18	−9.71	7.8	23.56
10	Kasarkhed	875	0.72	−5.5	20.8	28.26	959	0.32	−7.98	14.22	41.08
11	Mandwabudruk	841	0.91	−4.93	20.7	27.28	952	1.08	−9.36	27.56	42.68
12	Batwadi Budruk	987	1.41	−1.82	24.7	29.99	856	44	−11.94	13.61	31.66
13	Sangola	978	0.63	−6.05	17	24	1004	0.55	−7.76	19.5	45.9
14	Chatari	905	0.63	−3.76	16.1	22.95	954	0.3	−9.05	11.44	37.27
15	Pimpri dhangar	857	3.41	−2.41	59.2	63.2	857	3.41	−2.14	59.2	63.2
16	Uti	789	5.02	−3.67	64.4	62.36	789	5.02	−3.67	64.4	62.36
17	Pardi	1500	4.48	−3.17	57.4	53.6	1500	4.48	−3.17	57.4	53.6
18	Hiwrakhurd	899	1.17	−0.21	51.6	40.07	899	1.17	−0.21	51.6	40.07
19	Isoli	1200	1.83	−1.18	36.2	43.76	1200	1.83	−1.18	36.2	43.76
20	Karkhed	1006	1.68	−4.57	36.8	37.28	1006	1.68	−4.57	36.8	37.28
21	Ainkhed	894	1.06	2.01	42.4	35.13	894	1.6	2.01	42.4	35.13
22	Amdapur	987	0.64	−4.06	18.5	26.84	987	0.64	−4.18	18.5	26.84
23	Kawhaia	879	1.42	−2.75	28.6	34.75	879	1.42	−2.75	28.6	34.75
24	Mohadari	789	0.63	−5.88	21.7	21.11	789	0.63	−5.88	21.7	21.11
25	DhatraNaik	956	0.26	−9.06	7.7	12.66	956	0.26	−9.06	7.7	12.66
26	Wadali	645	0.5	−9.47	11.3	17.05	645	0.5	−9.47	11.3	17.05
27	Sirla	789	0.31	−0.01	10.8	18.47	789	0.31	−0.01	10.8	18.47
28	Shahapur	601	0.85	−8.31	18.7	23.75	601	85	−8.31	18.7	23.75
29	Dastapur	546	1.42	−8.85	26.6	29.94	546	1.42	−8.85	26.6	29.94
30	Loni	687	1.13	−0.9	29	38.13	687	1.13	−0.9	29	38.13
31	Lavkhed	489	1.49	−1.11	28.9	35.78	489	1.49	−1.11	28.9	35.78
32	TulangaKhurd	320	0.28	−8.51	9.1	14.85	320	0.28	−8.51	9.1	14.85
33	Tandi	823	0.63	−7.35	16	21.07	823	0.63	−7.35	16	21.07
34	Pimpalgaon	546	1	0.24	23.3	32	546	1	0.24	23.3	32
35	Modhapur	325	1.69	−3.82	32.8	39.01	325	1.69	−3.82	32.8	39.01
36	Satargaon	359	0.3	−7.11	9.5	16.88	359	0.3	−7.11	9.5	16.88
37	Ghui	456	1.48	−2.24	30.3	37.02	456	1.48	−2.24	30.3	37.02
38	Manegaon	325	0.86	−8.36	18	24.23	325	0.86	−8.36	18	24.23
39	Jhadegaon	312	0.86	−8.33	18.7	24.18	312	0.86	−8.33	18.7	24.18

(*continued*)

Table 2 | continued

		Pre-monsoon					Post-monsoon				
Sample no.	Village name	EC μs/cm	SAR meq/L	RSC meq/L	Na%	PI	EC μs/cm	SAR meq/L	RSC meq/L	Na%	PI
40	Palodi	589	0.3	−6.99	9.9	17.15	589	0.3	−6.99	9.9	17.15
41	Padsul	356	0.64	−4.85	19.1	26.52	356	0.64	−4.85	19.1	26.52
42	Golegaon Khurd	879	1	−4.1	22.8	31.26	879	1	−4.1	22.8	31.26
43	Manasgaon	879	0.43	−14	9.8	12.9	879	0.43	−14	9.8	12.9
44	Nimbi	564	1.96	2.92	39.7	48.12	564	1.96	2.92	39.7	48.12
45	Nimkhed	693	0.9	−4	20.8	26.67	693	0.9	−4	20.8	26.67

Table 3 | Classification of groundwater (Wilcox 1955)

Classification	Sample numbers	Number of samples	Percentage of samples
Very good to good	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 34, 35, 37, 38, 40, 41, 43	35	83.87
Good to permissible	31, 32, 33, 36, 39, 45	6	9.68
Doubtful to unsuitable	1, 15, 42, 44	4	6.45
Total		45	100

irrigation groundwater based on EC (Wilcox 1955) whereas Table 4 shows the salinity and alkalinity hazard based on classification criteria for irrigation water in a US salinity diagram.

Major ions

In this study the observed cations and anions showed the distribution in groundwater as: $Ca^{2+} > Mg^{2+} > K^{+}$ and $HCO_3^- > Cl^- > SO_4^{-2}$, respectively. The concentration of calcium ranges between 0.34–23.84 and 0–23.06 mg/L with a mean and standard deviation of 10.38, 8.60, and 6.55 and 5.67 mg/L during pre-and post-monsoon seasons in the study area. Calcium ions in the basaltic rock terrain develop from rock minerals such as feldspars and plagioclase (Singh *et al.* 2013b, 2015; Gautam *et al.* 2015). The concentration of magnesium value ranges varied from 1.9–9.12 and 2.07–10.21 mg/L with a mean of 4.73 and 5.20 mg/L in the area during pre- and post-monsoon. Bicarbonate is the dominant anion in the pre-monsoon which ranges between 1.03 and 9.57 mg/L with a mean of 4.01 mg/L and the dominant anion ranges between 1.07 and 11.16 mg/L post-monsoon.

Table 4 | Salinity and alkalinity hazard of irrigation water in US salinity diagram

Classification	SAR/EC	Sample numbers	Sample no.	Percentage of samples
C_2S_1	SAR-Low EC-Medium	4, 7, 9, 10, 13, 16, 18, 20, 22, 26, 27, 28 29, 30, 34, 35, 37, 38, 40, 41, 43	21	47.5
C_3S_1	SAR-Low EC-High	2, 3, 5, 6, 8, 12, 14, 17, 19, 21, 23, 24, 25 26, 31, 32, 33, 36, 39, 42, 44, 45	21	47.5
C_3S_2	SAR-Medium EC-High	11	1	1.50
C_3S_3	SAR-High EC-High	1, 15	2	3.50
Total			45	100

The highest chloride concentration ranges values obtained were 0.34–23.84 and 0–23.06 mg/L and the mean values were 10.38 and 8.60 in the pre-/post-monsoon season in the study area. During the pre-/post-monsoon, the concentration of sulphate ion ranges from 0.48–4.64 and 0.85–5.37 mg/L with a mean of 2.92 and 3.17 mg/L. Groundwater quality parameters such as chloride and bicarbonate were within the permissible limits. In this study area, some water quality parameters such as total dissolved solids (TDS), pH, sodium, calcium, magnesium and sulphate surpassed the permissible range at a few wells at certain periods of the year (Table 1). The sources of the above parameters are from rocks minerals (Singh *et al.* 2012; Rawat *et al.* 2017a, 2017b), namely feldspars, and plagioclase minerals in Deccan rocks.

GROUNDWATER CLASSIFICATION

Irrigation water quality

Irrigation water quality indices, namely SAR, sodium percentage (Na %), EC, RSC and Doneen's PI, have been computed. Ayers & Westcot (1994) have also suggested the parameters value for irrigation water quality. The observational well numbers W1–14, W16–W41, and W43 are suitable for agriculture purposes (Table 4). A total of 35 and six wells samples are very good to good and good to permissible, respectively. The small amount of plagioclase minerals and low salt content controls the quality. The well numbers W1, W15, W42, and W44 are unsuitable for irrigation and drinking purposes due to a large amount of plagioclase and the presence of salt-affected particles (Table 5). It was noted that the groundwater of a few wells was reported to be unsuitable for irrigation use due to the very high pH.

Table 5 | Irrigation groundwater classification based on EC (Wilcox 1955)

EC × 10^6 µs/cm at 25 °C	Water quality
<250	Excellent
250–750	Good
750–2000	Permissible
2000–3000	Doubtful
>3000	Unsuitable

Piper-trilinear diagram

Hydro-chemical facies can be divided on the basis of dominant ions by using the Piper-trilinear diagram. The concentrations of major ionic constituents of groundwater samples were plotted in the Piper-trilinear diagram (Piper 1944) to determine the water types. The cation and anion facies defines major-ion percentages and groundwater types, according to the domain in which they occur on the diagram segments (Gautam *et al.* 2015; Singh *et al.* 2015). The diamond-shaped fields between the two triangles denote the composition of groundwater with respect to both cations and anions. The observed well points for both the cations and anions are designed on the suitable triangle diagrams for understanding groundwater types.

Agriculture water

Quality standards

Good quality groundwater is required for irrigation of crops. Much soil and water management activity in the study area was performed in the past to improve the groundwater quality of the area. The suitability of groundwater depends upon many factors: water, soil classification, salt tolerance characteristic of the plants and agriculture crops, climate change and drainage parameters (Kumar *et al.* 2018). Further, it also depends on soil quality and erosion rates. Figure 3 shows the rating of water in relation to salinity and sodium hazard of Man River basin (Wilcox 1954).

Irrigation indices

Sodium adsorption ratio (SAR)

The SAR parameter is an important parameter for irrigation purposes. An extreme quantity of involved ions such as sodium, bicarbonate, and carbonate has a direct impact on groundwater and direct effects on plants and crops. Saline water has an impact on soil fertility and its physical and chemical characteristics and the productivity of crop yield decreases under saline and dry land conditions. Salinity of water reduces the osmotic treatments of crops and plants and thus (Saleh *et al.* 1999; Singh *et al.* 2015; Rawat *et al.* 2018a, 2018b, 2018c, 2018d, 2018e; Nemčić-Jurec *et al.* 2019). The SAR is the measure

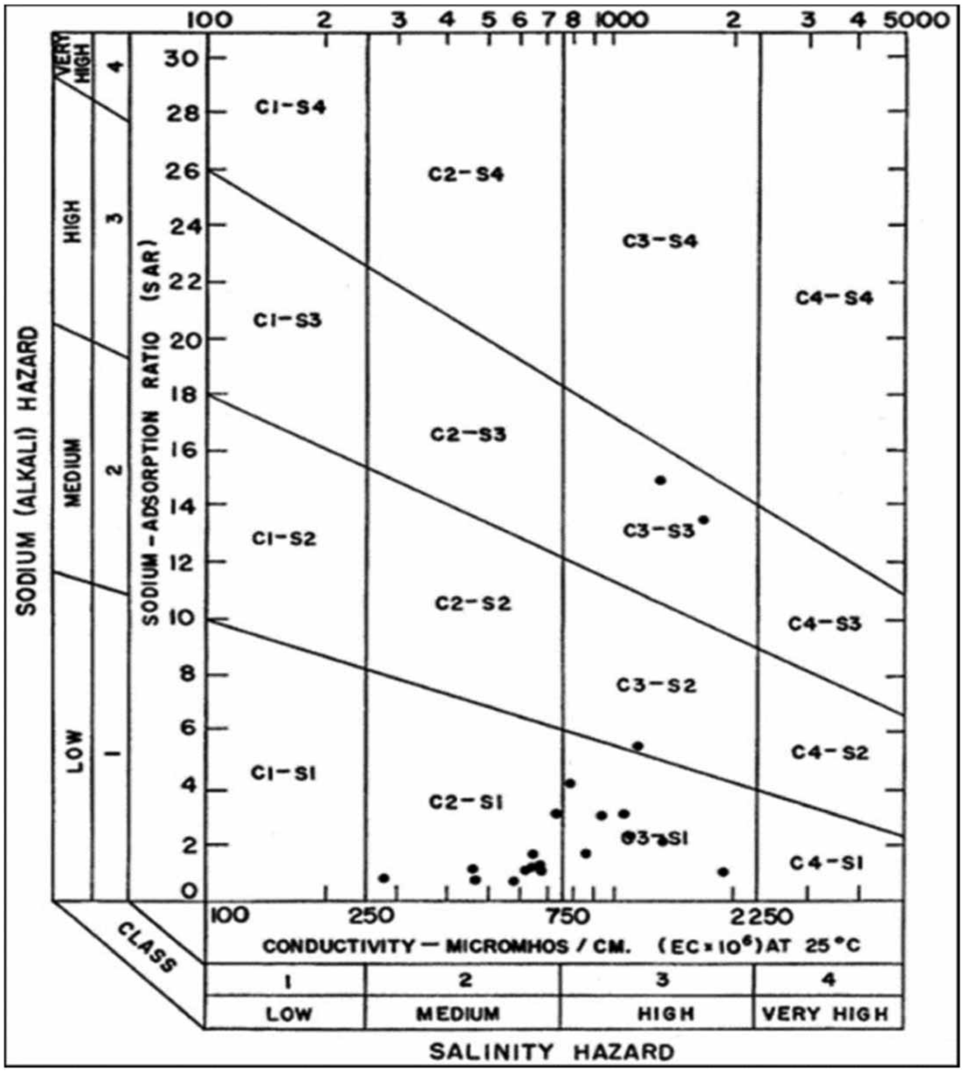

Figure 3 | Wilcox's graphic (USSL diagram) for classification of irrigation waters (Wilcox 1954).

of the amount of sodium (Na^+) relative to calcium (Ca^{2+}) and magnesium (Mg^{2+}) in the water extracted from a saturated soil paste. It is the ratio of the Na concentration divided by the square root of one-half of the Ca + Mg concentration. SAR is calculated from Equation (3):

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

where Na^+, Ca^{2+}, and Mg^{2+} are in meq/L.

On the basis of SAR ranges, irrigation water can be classified into four classes as SAR < 10 (Ideal or Excellent), 10–18 (Good), 18–26 (Doubtful), >26 (Unsuitable). SAR also influences the percolation time of water in the soil. Therefore, the low value of SAR of irrigation water is desirable. Soils that have values for a SAR of 13 or more may have an increased dispersion of organic matter and clay particles, reduced saturated hydraulic conductivity and aeration, and a general degradation of soil structure.

In this study, most of the samples fall under the C2S1, low SAR and medium EC parameters and the C3S1 low value of SAR and high value of EC, both classes showed 47.5% samples (21 samples for each category, respectively (Table 4). One sample shows C3S2 types as 1.50%, and two samples are presented in C3S3 as 3.50%. It shows a very high salinity (C2) and low sodium hazard (S1) for pre- and

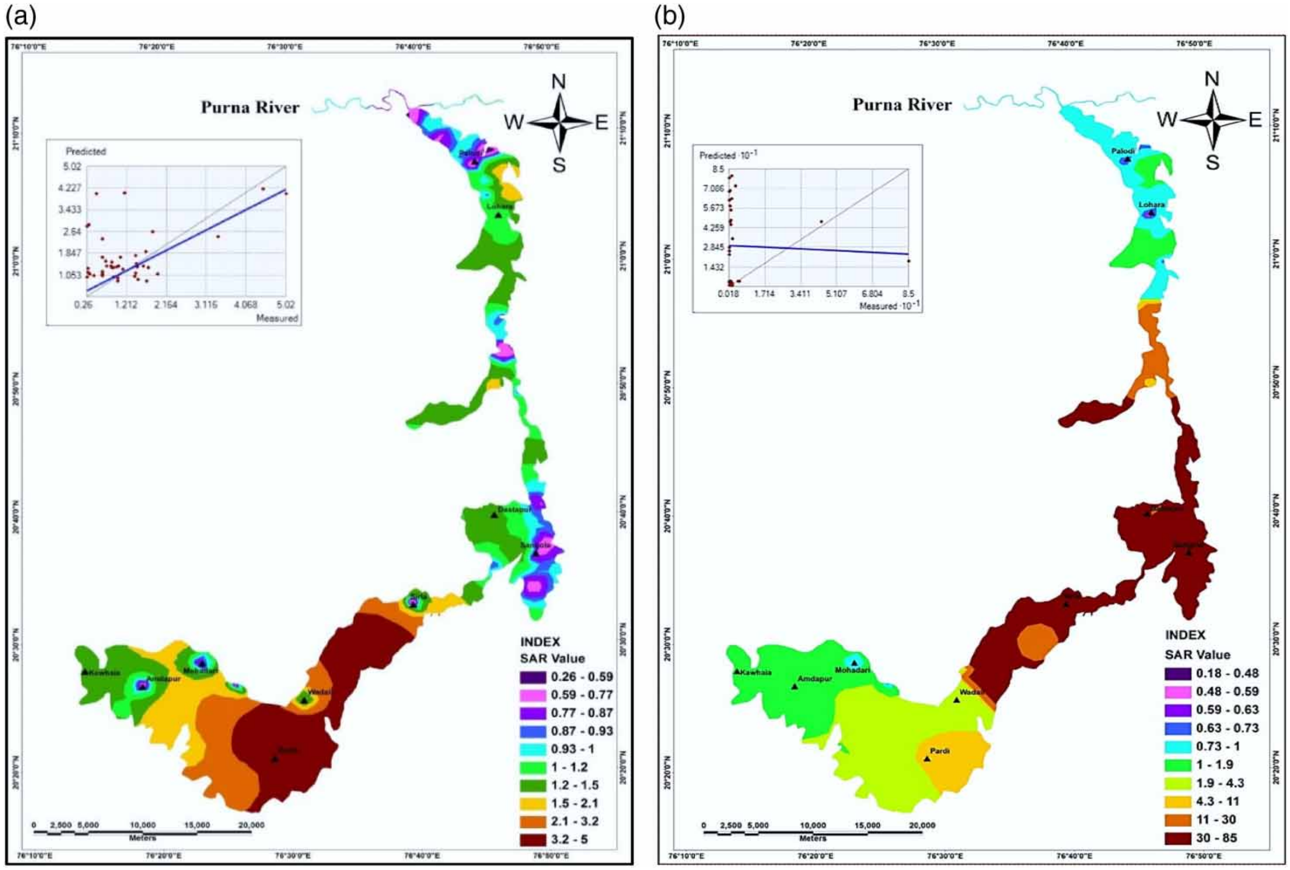

Figure 4 | Spatial distribution of SAR (mg/L) during (a) pre-monsoon and (b) post-monsoon.

post-monsoon seasons. The study of SAR and EC values for pre- and post-monsoon season data were plotted in a graphical diagram (Wilcox 1955; Figure 4(a) and 4(b)). Figure 4 shows that a large amount of the groundwater samples decrease under the field of C2S1 and C3S1 during the years of pre-/post-monsoon season data and one sample falls in C3S2 and two samples are in C3S3 (Figure 4(a) and 4(b)). Groundwater samples fall into the C2S1 and C3S1 category showing medium to high salinity and low alkalinity. The groundwater of these categories can be used for agriculture purposes due to less harmful effects. The C3S2 category water has high salinity and medium alkali hazards and hence needs treatment before use for irrigation purposes (Table 4). The SAR statistics of pre-monsoon showed minimum, maximum, mean, and standard deviation values as 0.26, 5.02, 1.19, and 0.96 and for post-monsoon, 0.18, 85, 3.91 and 13.79, respectively. The pre-monsoon groundwater quality is good as compared with post-monsoon season because during December–May, the salt water content increases due to the pumping of groundwater for irrigation purposes. In this season, heavy to medium rainfall has been observed and the earth surface particles have transferred in groundwater and aquifer zones through the fracture of rocks in the Man River catchment.

Electrical conductivity (EC)

The higher value of EC in both the seasons (pre-monsoon and post-monsoon) is due to a high rate of evaporation which showed that groundwater has a high electrolyte concentration under pre- and post-monsoon seasons. According to Wilcox's (1955) classification, none of the groundwater samples fall in an excellent class for irrigation purposes and sustainable crop development reduces salinity hazards and dry land area, while the majority of the groundwater samples fall in permissible ranges under pre- and post-monsoon. The

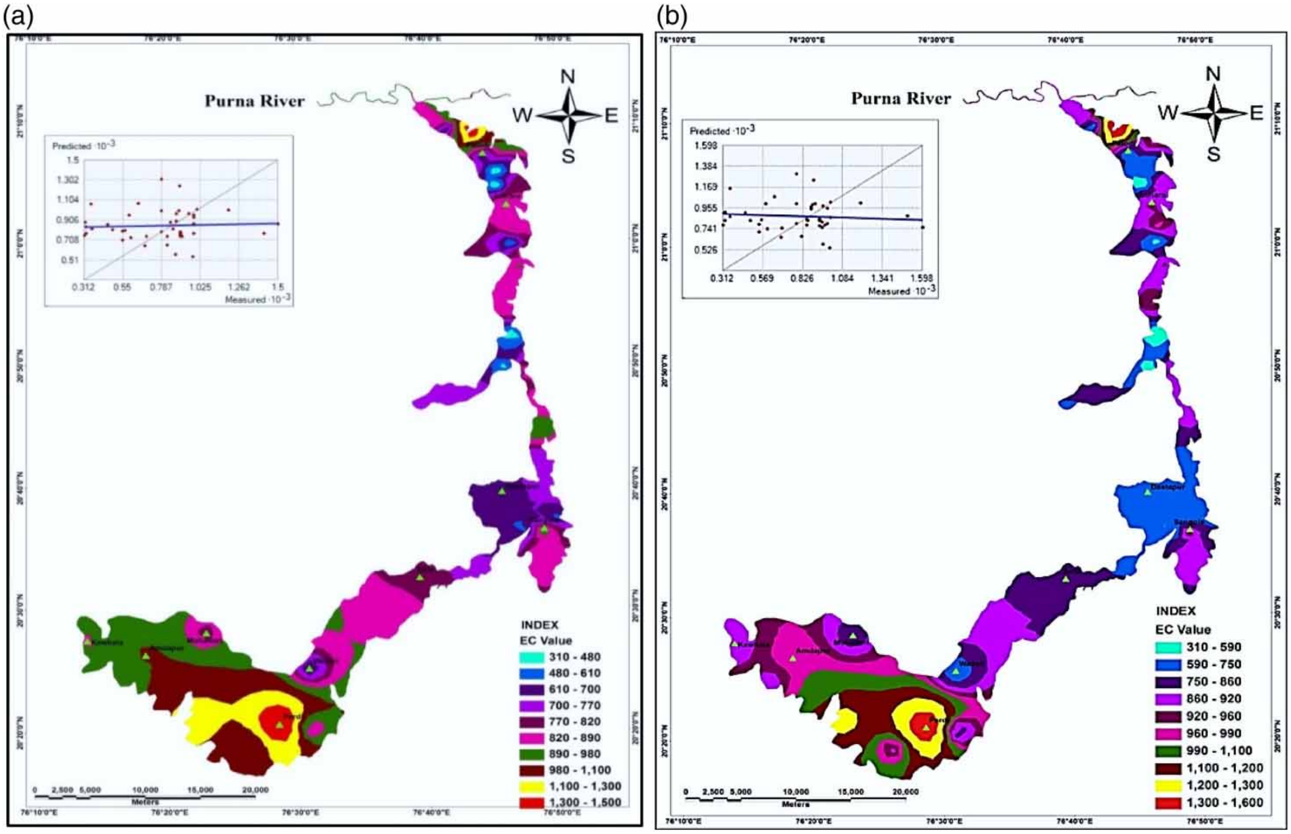

Figure 5 | Spatial distribution of EC (μs/cm) during (a) pre-monsoon and (b) post-monsoon.

salinity hazard is an issue at the few well locations where the EC is very high. The study of additional salinity interferes with the absorption of groundwater samples and the nutrients management from the soil and by dropping the osmotic activity of crops and plants. EC distribution in groundwater ranges from 312 to 1598 μs/cm at 25 °C. The classification of groundwater for irrigation purposes depends upon EC value as per Wilcox (1955). EC plots are given in Figure 5(a) and 5(b). Table 5 shows irrigation groundwater classification based on EC (Wilcox 1955).

Exchangeable sodium percentage (ESP)

The sodium percentage (Na%) is calculated using the formula given in Equation (4):

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

(all the ion concentrations are expressed in meq/L).

The ionic concentrations are explained as per meq/L unit. The sodium percentage (Na%) shows the groundwater quality is in the category of 'very good to good' in some wells of the Man River catchment (Figure 6(a) and 6(b)). The Wilcox diagram (Figure 7) shows groundwater quality for irrigation use. The study of sodium concentration plays an important role in evaluating water quality parameters for irrigation purposes (Wilcox 1955; Tijani 1994; Singh *et al.* 2015; Rawat *et al.* 2018a). The %Na statistical value as minimum, maximum, mean and standard deviation value was 7.7, 64.4, 25.81 and 13.25 in pre-monsoon and 7.7, 64.4, 2418 and 13.62 in post-monsoon, respectively in the saline zone area, respectively (Table 6). Table 6 shows irrigation groundwater quality based on %Na.

Permeability index (PI)

The groundwater samples were assessed on the basis of PI values for the suitability of wells for irrigation, for irrigation

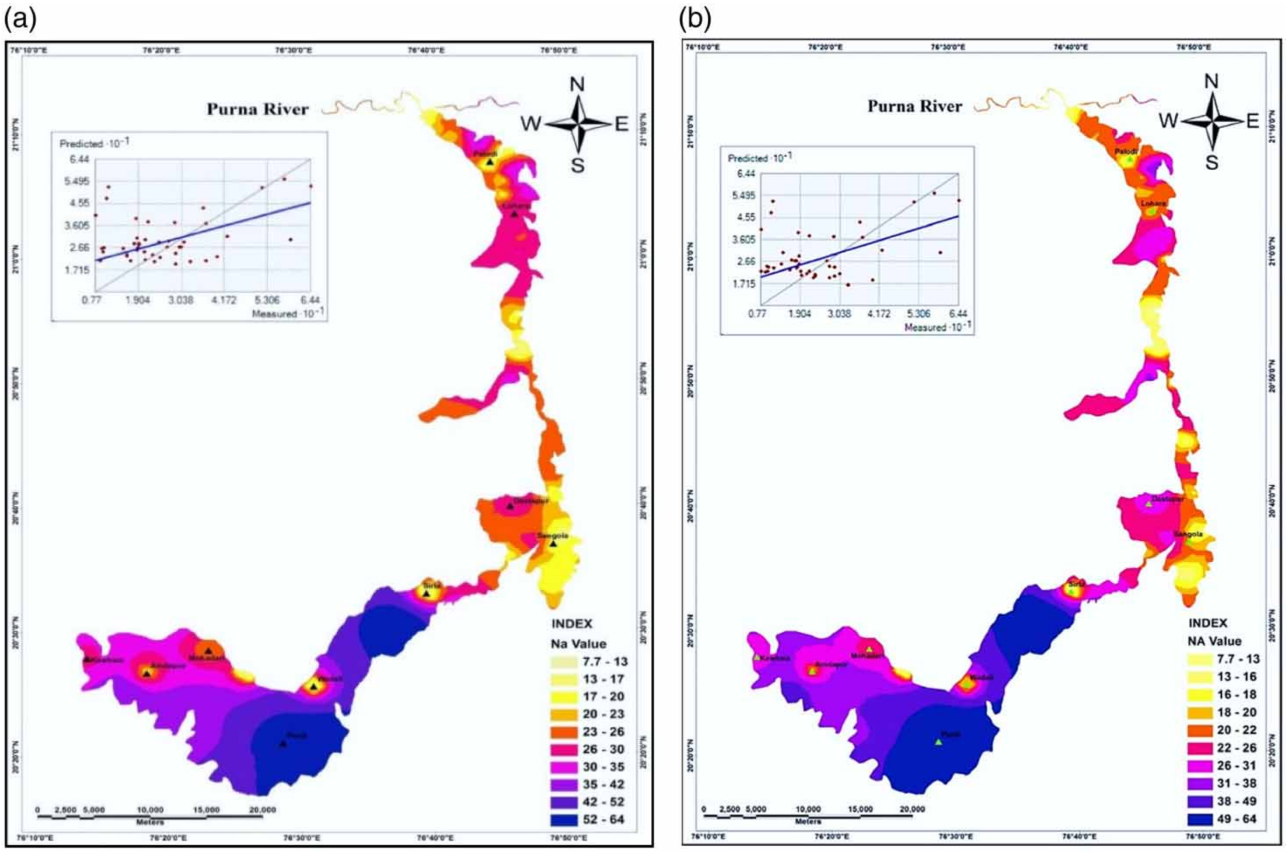

Figure 6 | Spatial distribution of Na% during (a) pre-monsoon and (b) post monsoon.

purposes in the agronomy crops and plants of the saline zone area. The long-term use of groundwater affects the soil fertility and permeability (Rawat *et al.* 2018a; Nemčić-Jurec *et al.* 2019). These concentrations of ions, such as Na^+, Ca^{2+}, Mg^{2+} and HCO_3^-, rise in the soil due to groundwater irrigation and high rates of evaporation (Singh *et al.* 2015; Rawat *et al.* 2018a). Donne (1962) developed criteria for determining the quality of water for irrigation based on PI in the pre- and post-monsoon season data. Soil permeability has been affected due to excess irrigation from groundwater in the long term and low crop yield (Ishaku *et al.* 2011; Nemčić-Jurec *et al.* 2019) and is expressed as Equation (5):

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

(all the ion concentrations are expressed in meq/L).

According to Doneen (1964), PI can be categorized into three classes, class I (>75%, suitable), class II (25–75%, good) and class III (<25%, unsuitable). Water under class I and class II is recommended for irrigation while the third category of PI is classified as PI = 25% and is not recommended for irrigation.

The majority of the water samples fall in class I, which implies that the groundwater quality is good for irrigation purposes. The distribution of PI values has been found to be higher in Wadak, Sirla and Mohadari villages, however lower values were observed in the Datranaik village of the Man River catchment (Figure 8(a) and 8(b)).

Residual sodium carbonate content (RSC)

The suitability of water for irrigation is often affected by the available quantity of bicarbonate and carbonate in excess of

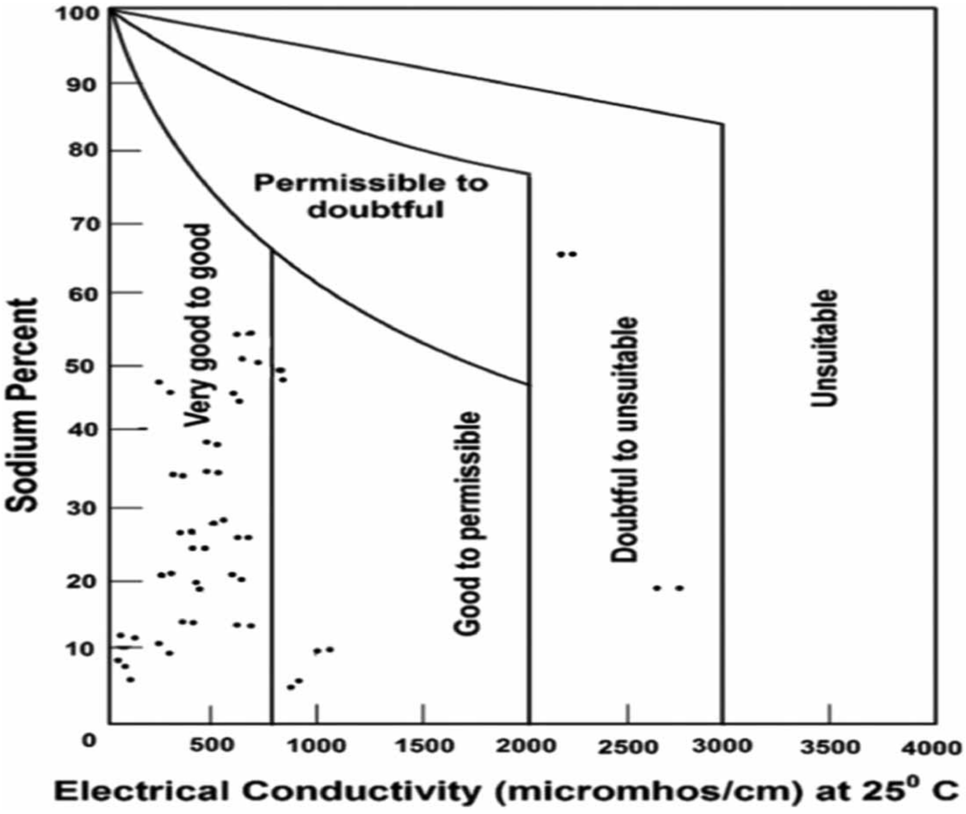

Figure 7 | Classification of irrigation waters (after Wilcox 1955).

Table 6 | Irrigation quality of groundwater based on sodium percentage

%Na	Classification	Sample numbers	Number of sample	Percentage of samples
40–60	Very good	4, 7, 9, 10, 13, 16, 18, 20, 22, 26, 27, 28, 29, 30, 34, 35, 37, 33, 36, 39	19	45.93
60–80	Good	2, 3, 5, 6, 8, 12, 14, 17, 19, 21, 23, 24, 25, 26, 31, 32	16	37.89
20–40	Permissible	11, 38, 40, 41, 43, 45	6	9.68
<20	Doubtful	1, 15, 42, 44	4	6.45
>80	Unsuitable	Nil		
	Total		45	100

alkaline earths (Singh *et al.* 2013a). When the total carbonates and bicarbonates are in excess of the total Ca^{2+} and Mg^{2+}, there may be a possibility of complete precipitation of carbonates, bicarbonates ions and Ca^{2+} and Mg^{2+} in groundwater. The RSC index has been used to quantify the effects of carbonate and bicarbonate using Equation (6). On the basis of the RSC range, it has been classified into three classes as follows: RSC < 1.25 (low), 1.25–2.5 (medium) and >2.5 (high). RSC is expressed as Equation (6):

$$RSC = (HCO_3^- + CO_3^{2-}) - (Ca^{2+} + Mg^{2+}) \quad (6)$$

A high range of RSC in irrigation water means an increase in the adsorption of sodium on the soil. Water having RSC > 5 is not recommended for irrigation because of the damaging effects on plant growth, generally any

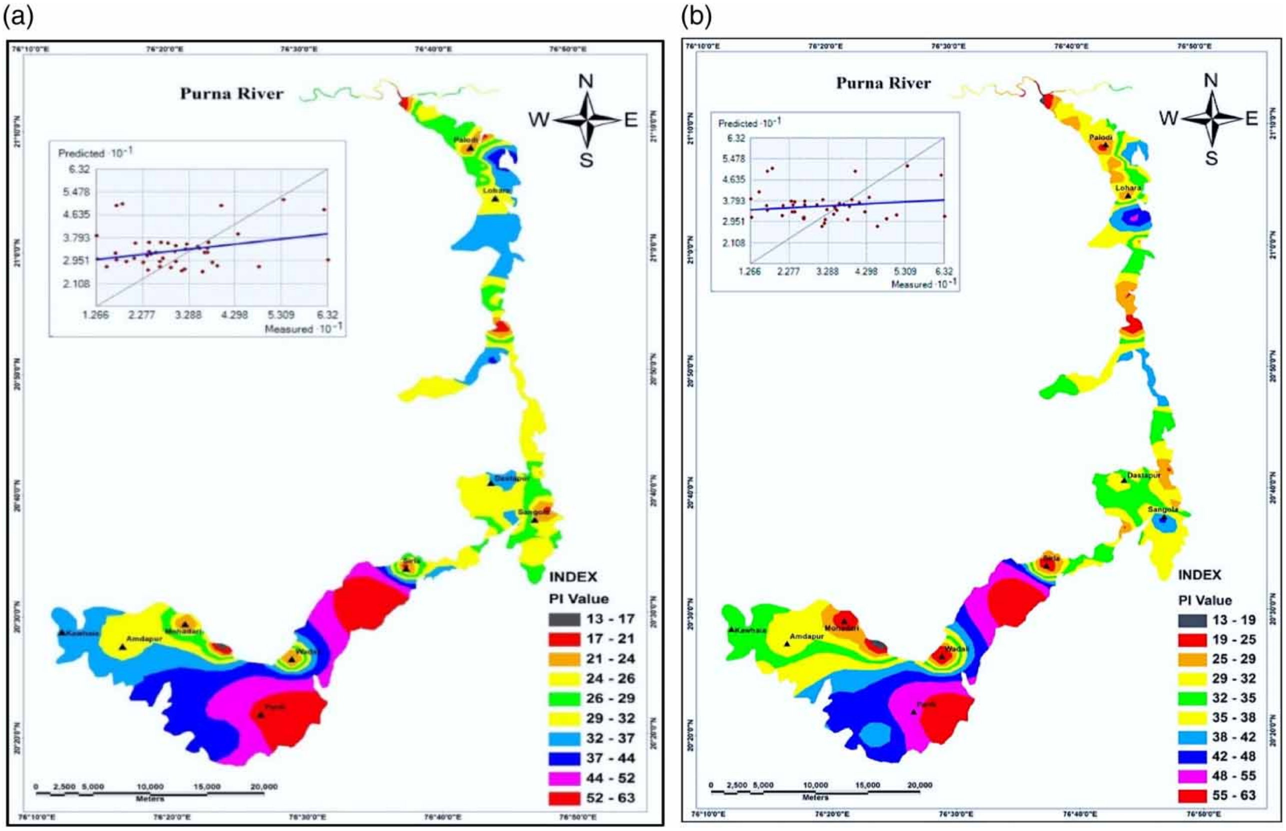

Figure 8 | Spatial distribution of PI% during (a) pre-monsoon and (b) post-monsoon.

source of water where the RSC is higher than 2.5 is not considered suitable for agriculture purposes, and water <1.25 is recommended as safe for irrigation purposes. Higher values of RSC in water has led to fast absorption of sodium in soil (Singh *et al.* 2013a). If the RSC values >5 $meqL^{-1}$ then these water sources are considered to be harmful for the growth of plants, whereas with RSC values >2.5 $meqL^{-1}$, water is not suitable for irrigation purposes.

Mapping of water quality parameters and recommendations

The results of IDW interpolation methods are extremely subjective by this weighting power (Mueller *et al.* 2001). It would be better to analyze and spatially generate maps of the groundwater quality. The groundwater quality spatial maps clearly show suitable or unsuitable areas in the dry land of Man River catchment. In the last 2–3 decades, many farmers have suffered from saline and poor groundwater quality. These groundwater quality maps can be used for watershed management, rainwater harvesting activity and calibration and validation of water quality models in the Man River catchment. Finally, it is determined that there is an absence of proper monitoring of groundwater quality, and a regular chemical analysis is essential to predict the suitability of groundwater for drinking and irrigation purposes during pre- and post-monsoon season. In this study area, the aqua filter will be fitted on the 45 observation wells for sustainable water resources management as the increased use of groundwater for irrigation is increased to improve the crop yield production and better planning for protection of drinking water during a dry spell period.

The contour maps of the spatial distributions of the hydro-chemical parameters of the study area are shown in Figure 3(b). The interaction of soil-rock-water due to weathering, geochemical reactions, alkaline nature of water, ion-exchange, high variability in temperature range and anthropogenic activities are mostly controlled processes of elevated concentration of ions in the groundwaters of the study area (Singh et al. 2013a, 2013b; Rawat et al. 2018a, 2018b, 2018c, 2018d, 2018e). The anthropogenic contribution of nitrate and chloride is high in a few locations. Weathering of limestone, dolomite, gypsum and anhydrite and cation exchange processes release Ca^{2+} and Mg^{2+} ions into groundwater (Singh et al. 2012). The possible sources of Na^{+} in groundwater are dissolution of rock salts and weathering of sodium bearing minerals (Singh et al. 2015). The HCO_3^- concentration in groundwater is derived from carbonate weathering as well as dissolution of carbonic acid in the aquifers (Singh et al. 2009, 2010, 2012, 2013a, 2013b; Gautam et al. 2015; Nemčić-Jurec et al. 2019).

CONCLUSIONS

The groundwater quality was evaluated using irrigation indices such as SAR, Na%, RSC and PI. The majority of the wells fall under moderate to unsuitable category of water for irrigation purposes. The majority of the water types are Ca–Na–Mg and Cl–SO_4 facies. The C2-S1 and C3-S1 categories have 47.5%. The groundwater quality for irrigation is very good in the hard-basaltic rock area. The crops such as soybean, gram, and cotton under basaltic rock and dry land areas are recommended for growth. However, the PI value showed that almost all the groundwater wells are appropriate for crops, so GIS maps will be helpful for finding suitable locations and wells for execution of the sprinkler irrigation systems. A positive solution would be continuous groundwater quality monitoring in the pre- and post-monsoon seasons. The detailed study of hydro-geochemical analysis can be used for ecological use of groundwater resources and watershed management in the Man River catchment.

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First received 4 March 2019; accepted in revised form 23 June 2019. Available online 31 July 2019