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ORIGINAL ARTICLE

Spatial variations and trend analysis of groundwater salinity along coastal aquifers of Mundra-Kachchh over a decade—using thematic maps and GIS mapping

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Abstract
Water is one of the most basic entities, especially in semiarid regions where low precipitation and limited surface water resources bring more emphasis on the use of groundwater leading to endangering and overexploitation. Therefore, quantity with monitoring of groundwater quality at regular intervals becomes of utmost importance for understanding its suitability for drinking and irrigation. This study aims in understanding spatial variations and their trend in terms of quality over a decade (2010–2020) using different hydrochemical parameters in the vicinity of the coastal tracts of the Mundra block. Samples were analyzed for TDS, pH, EC, TH, major cations, and anions. Drinking suitability was identified by correlating parameters with WHO, BIS standards and by preparing WQI maps. Irrigational suitability was found by SAR, RSC, KI, Na %, MH, and PI. Reduced water level (RWL) values represented a further increase in the reversal flow of groundwater in a decade leading to an increment in salinity and seawater intrusion. The study area in most of the analysis is possessing much higher values above safer limits when compared to 2010 and 2020, making the water very much unacceptable for drinking and irrigation. The major cause in the area is overexploitation and unconditional deeper drilling, resulting in an increase in coastal salinity and seawater intrusion. The use of such water tends to harm agriculture, soil condition as well as human health.

Keywords Semi-arid · Spatial variations · Salinity · Coastal aquifer · Kachchh

Introduction

Water is one of the most basic entities on the earth system for the sustenance of mankind. Freshwater resources are crucial and are used for various motives such as drinking, household, agricultural and industrial sector. One of the major contributors to governing all the sector's needs is groundwater due to cheap and easily available exploring technologies for a freshwater source. Out of 37 Mkm^3 estimated fresh water on our planet earth, groundwater contribution stands at 22% which nearly accounts for 97% of potential potable water for human consumption (Foster 1998). With the increase in demands for freshwater, groundwater drafting also increases causing an imbalance between exploitation to recharge leading to endangering and overexploitation of this renewable resource, hence bringing deterioration and depletion in aquifer systems. In particular, in arid to semi-arid regions where low precipitation and limited surface water resources bring more emphasis on the use of groundwater as a potential freshwater source (Scanlon et al. 2006). This issue further peaks upward in a coastal region of arid to the semiarid regime where aquifers are of shallower to moderate depth and there is always a chance of increase in coastal salinity, seawater ingression, and water pollution due to over-drafting, which ultimately degrades the quality of groundwater (Chen et al. 2021, 2020, 2017; Qian et al.

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2020). Therefore, with the quantity of groundwater, monitoring groundwater quality at regular intervals is of utmost importance for understanding its suitability for drinking, irrigation, and other daily needs. This kind of study also helps in understanding long-term behavior and variations in the quality of coastal aquifers, suitability of water for drinking and irrigation, salinity ingress or regress, seawater intrusion further moving landwards or retreating, etc. Earlier many researchers have conducted studies related to groundwater quality assessment, especially throughout India (Chintalapudi et al. 2017; Gautam et al. 2015; Jasrotia et al. 2018; Praveena et al. 2010; Xu et al. 2019; Zhang et al. 2019, 2020). Avtar et al. (2013) carried out hydrochemical studies for determining the suitability of groundwater for various purposes. Similarly, Lapworth et al. (2017) determined the hydrochemistry of top aquifers ranging up to 160 m. Tiwari et al. (2017) described spatial variations in groundwater quality parameters.

Kachchh district of Gujarat state has seen a great amount of growth over the last two decades in the industrial sector, especially along southeastern coastal tracts. Mundra block has become one of the crucial parts of the industrial and agricultural sector. As a result, there has been a great amount of increase in demands for freshwater which is mostly fulfilled by the extraction of groundwater and through the piped water supply. This could make coastal aquifers highly vulnerable to deterioration and contamination by salinity water ingress, seawater intrusion, etc. Therefore, this study was aimed at understanding spatial variations and its trend in terms of quality over a decade using different hydrochemical parameters in the vicinity of the coastal tracts of Mundra block to understand water suitability for drinking, irrigation, and changes in the water quality over a decade along with groundwater flow variations for this coastal aquifer system which will help in identifying the behavior of coastal salinity and seawater ingress or regress.

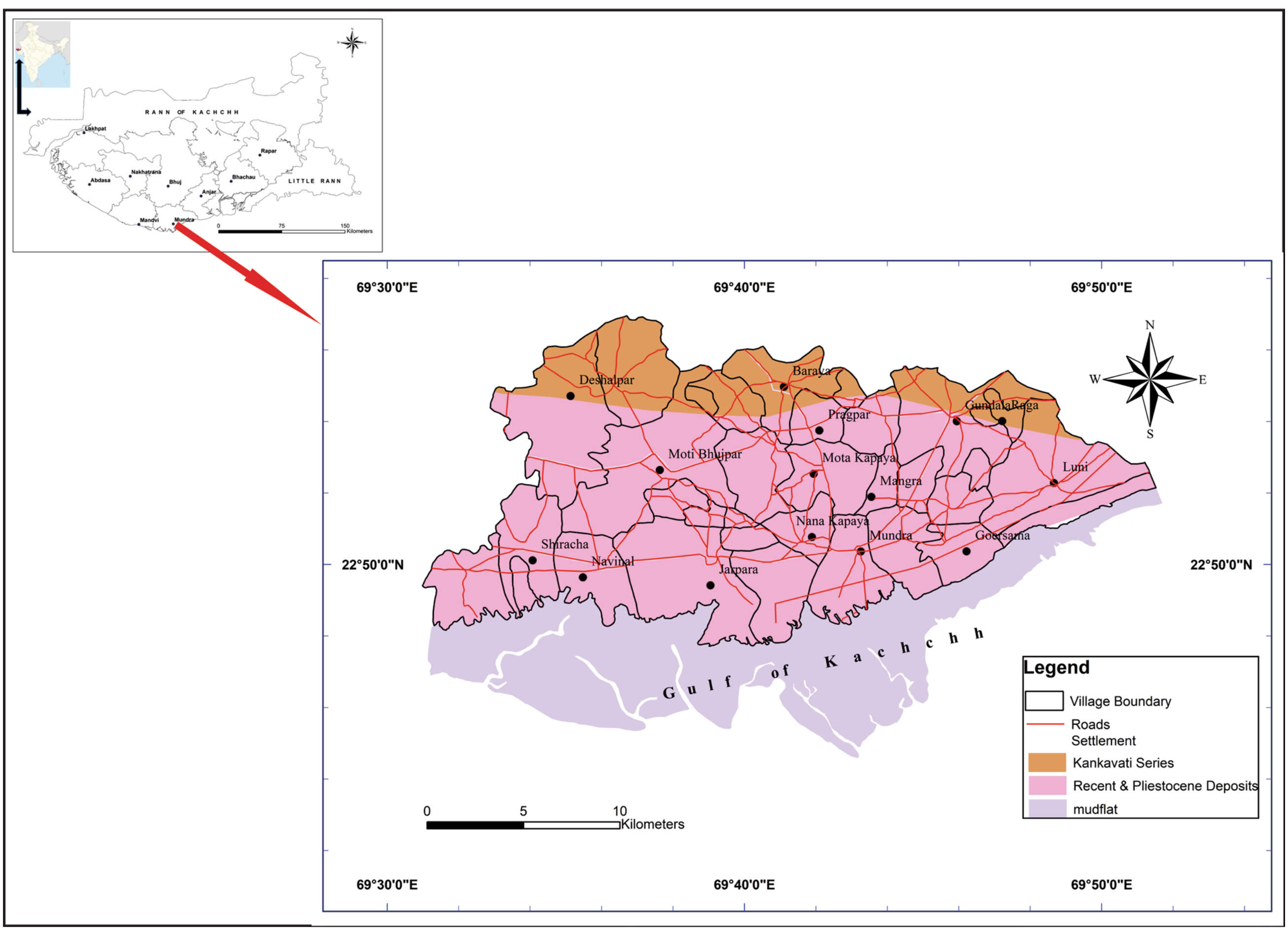

Fig. 1 Geological map of study area (modified after Biswas 2016)

Study area

The study is located between 22º 45′–22º 58′ and 69º 30′–69º 50′ longitude in the southern region of the Kachchh basin in Mundra block near the coast (Fig. 1). This area covers about 350 sq km area. This area also falls under Special Economic Zone (SEZ) as declared by the Government of Gujarat under the Government of India's Industrial Development Policy (2005). Three major rivers flowing southward drains through the study area and debouches their water into the Gulf of Kachchh viz. Naagmati, Surai, and Bhukhi rivers. Due to the semiarid nature of the study area, the precipitation is quite low with an average annual rainfall of 361 mm which occurs mostly during the southwest monsoon. Temperatures are also high throughout the year standing at about 38–40 ℃ in summer and 12–14 ℃ in winter.

Geologically, the study area is marked by Deccan traps of late Cretaceous age which form the basement for Tertiary and Quaternary sequences. Figure 1 shows the geological map of the study area possessing rocks of Pliocene age consisting of Kankavati series sandstones with intercalations of clay pockets, which are exposed in the upper portion of the study area. The sandstones and clay pockets show unconfined to semiconfined nature, and it forms a prolific aquifer in the coastal area for extraction of groundwater. The quaternary fluvial deposits overlie upon tertiary rocks and are exposed in the southern region of the study area. These quaternary deposits show fragile and unsorted nature with a mixture of sand and clay which forms a shallow unconfined aquifer in this region (Biswas 1993).

Methodology

The methodology adopted was divided into two components: (1) data collection and (2) data analysis.

Data collection

The present study scrutinized physiochemical parameters of Pre-monsoon 2010 and Pre-monsoon 2020 for 21 samples. Pre-monsoon 2010 physiochemical analysis of groundwater was acquired from research work conducted by Bhimani (2013), while for Pre-monsoon 2020, 21 groundwater samples were collected from borewells and dug-cum borewells in a high-quality polyethylene bottle of 1 L. The collected samples were systematically packed, sealed to avoid any sort of adulteration, and were brought to the laboratory for further analysis. Total dissolved solids (TDS), pH, and electrical conductivity (EC) were determined and collected in the field itself using a multi-parameter probe.

Data analysis

Hydrochemical Characterization

Collected water samples from the field were examined for total hardness as $CaCO_3$ (TH), major cations (Na^+, K^+, Ca^{2+}, Mg^{2+}), and anions (HCO_3^-, CO_3^{2-}, Cl^-, SO_4^{2-}, NO_3^-) using Standard Analytical Procedures given by (APHA 2005). Among these analyzed ions Na^+ and K^+ were determined using a Flame photometer. Ca^{2+}, Mg^{2+}, Cl^-, CO_3^{2-}, HCO_3^-, and total hardness were examined using titration methods. SO_4^{2-} was evaluated using UV spectrophotometer. To assess drinking water suitability for 2010 and 2020 were compared with WHO (2017) and BIS (1998) standards. TDS, Cl^-, and Na^+ maps were prepared to understand spatial distribution for 2010 and 2020 in terms of water quality and its suitability for drinking using ArcMap 10.4.1 software by Inverse Distance weighted (IDW) techniques.

Water Quality Index (WQI)

The water quality index was calculated and determined by using Eqs. (1), (2), and (3) and through classification provided by Brown et al. (1972). The steps adopted for water quality index calculations are as per Brown et al. (1972) using the weighted arithmetic method.

Step 1: Calculate the unit weight for each parameter by using the formula.

$$Wn = \frac{K}{Sn} \text{ where } K = \frac{1}{\frac{1}{S1} + \frac{1}{S2} + \frac{1}{S3} + \ldots + \frac{1}{Sn}} = \frac{1}{\Sigma\frac{1}{Sn}} \tag{1}$$

Sn = Standard desirable value of the nth parameter. On summation of all selected parameters unit weight factors, $Wn = 1$ (unity).

Step 2: Calculate the Sub-Index (Qs) value by using the formula

$$\mathrm{Q}n = \frac{[(Vn - Vo)]}{[(Sn - Vo)]} \times 100 \tag{2}$$

where Vn = mean concentration of nth parameters, Sn = standard desirable value of the nth parameters, Vo = actual values of the parameters in pure water (generally $Vo = 0$, for most parameters except for pH).

Step 3: Combining Step 1 and Step 2, WQI is calculated as follows:

$$\mathrm{OverallWQI} = \frac{\Sigma WnQn}{\Sigma Wn} \tag{3}$$

The index was calculated for each well for the years 2010 and 2020. These index values were then plotted in ArcGIS software and were interpolated using Inverse Distance Weighting (IDW) to prepare WQI maps for 2010 and 2020.

Trilinear piper plot

Trilinear piper plot (Piper 1944) helps in representing complex hydrochemical data to provide an insight in determining the various types of groundwater with its dominating constituents dissolved in water. Trilinear piper plot consists of two triangular fields one for the cations and the other for the anions with one central diamond plot. All cations (Ca^{2+}, $Na^{+}+K^{+}$, Mg^{2+}) and anions ($CO_3^{2-}+HCO_3^{-}$, Cl^{-}, SO_4^{2-}) represented in meq/L were plotted on a piper plot to determine the geochemical evolution of the water during a decade with the help of Grapher software. Diamond field is classified into four categories as represented in Fig. 7 as I–IV.

Irrigation suitability

To understand the type of salinity changes during a decade within these coastal aquifers, Piper's plotting was carried out for major ions using Grapher software. Similarly, to identify groundwater suitability for irrigation and changes during a decade, different irrigation parameters analyses were conducted such as Electrical Conductivity (EC), Sodium Absorption Ratio (SAR), United States Salinity laboratory (USSL) diagram, Residual Sodium Carbonate (RSC), Kelly's Index (KI), Sodium (Na) Percent, Magnesium Hazard (MH) and Permeability Index (PI).

(a) ***Sodium %***

The Na^{+} percentage is an essential irrigation parameter to describe the hazards of sodium in water systems. The higher presence of sodium in water tends to replace Ca^{2+} and Mg^{2+} in the soil causing variations in soil structure. Higher concentrations tend to reduce the permeability of the soil which ultimately reduces water circulation and air exchange (Kumar et al. 2007) which inhibits the growth of crops. Sodium percent was calculated in the study area using the given Eq. (4) as follows:

$$\text{Sodium\%} = Na^{+} + K^{+} \times 100/\left[Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}\right] \tag{4}$$

Wilcox (1955) classification for sodium % describes < 20 to be in excellent, 20–40 in good, 40–60 in permissible, 60–80 in doubtful, and > 80 to be under the unsuitable category.

(b) ***Sodium Absorption Ratio (SAR)***

The sodium absorption ratio is one of the crucial parameters to determine the eligibility of groundwater for the use of irrigation as it has a direct relation with the capacity of the water that a soil can absorb (Todd 1980). Higher sodium reduces the water absorbance capacity of the soil, and extreme input of sodium can destroy complete fertility and structure of the soil bringing low yield in crop production. Therefore, the SAR value was calculated using Eq. (5) given by Richards (1954). All the values are in meq/L.

$$\text{SAR} = \frac{Ca^{2+}}{\left[\left(Ca^{2+} + Mg^{2+}\right)/2\right]^{0.5}} \tag{5}$$

Richards (1954)-based classification of SAR values is as follows: < 10 is considered to be excellent, 10–18 good, 18–26 doubtful, and > 26 unsuitable for the irrigation.

(c) ***Residual Sodium Carbonate (RSC)***

Higher concentrations of carbonate and bicarbonates in irrigational water have a great impact on crop yield and plants. High values of RSC tend to precipitate magnesium and calcium causing more adsorption of sodium on the soil leading to higher concentration values of sodium (Eaton 1950). Increased values of RSC also cause the burning of leaves which results in lowering of photosynthesis process and bringing low yield (Ramesh and Elango 2012). All the parameters required for analysis were taken in meq/L. To calculate RSC, Eq. (6) was used.

$$\text{RSC} = \left(HCO_3^{-} + CO_3^{2-}\right) - \left(Ca^{2+} + Mg^{2+}\right) \tag{6}$$

Richards (1954)-based classification of RSC values is as follows: < 1.25 is found to be safe/good, 1.25–2.50 marginal/doubtful, 2.5–5 unfit for irrigation, and > 5 is considered severely harmful to plants and human health.

(d) ***Kelly's Index***

Kelly's index is defined as a ratio of

$$Na^{+}/(Ca^{2+} + Mg^{2+}) \tag{7}$$

with the values taken in meq/L. This ratio is used for defining the suitability of water for irrigation. Based on Kelly (1946), concentrations < 1 are considered to be safe, 1–2 to be negligible, and values > 2 suggest an excess of sodium being present making it unsuitable for irrigation.

(e) ***Magnesium Hazard (MH)***

Ca^{2+} and Mg^{2+} are considered to be in equilibrium within the groundwater systems. Higher concentrations of magnesium cause soil to turn into alkaline, impermeable, and bring low crop yield. Based on Paliwal (1972), MH value > 50% is considered to be suitable for irrigation, while < 50% is considered to be completely unsuitable for irrigation.

$$\text{Magnesium Hazard (MH)} = \text{Mg}^{2+} \times 100/\left(\text{Ca}^{2+} + \text{Mg}^{2+}\right) \tag{8}$$

(f) ***Permeability Index (PI)***

The permeability of the soil is highly affected by concentrations of cations and anions. Higher concentrations of Ca^{2+}, Na^{+}, Mg^{2+}, and HCO_3^- reduce the permeability of the soil. Therefore, the permeability index is essential to be identified for the irrigational sector. Doneen's (1964) classification was used for identifying suitability which describes percentages, > 75 is considered to be of class-I (good) category, 25–75 under class-II (suitable), and < 25 under class-III (unsafe). Equation (9) was used to derive PI was as follows:

$$\text{PI} = \left[\text{Na}^{2+} + \left(\text{HCO}_3^-\right)^{0.5}\right] \times 100/\left[\text{Na}^{2+} + \text{Ca}^{2+} + \text{Mg}^{2+}\right] \tag{9}$$

Groundwater flow, recharge, and discharge areas

The movement and circulation of groundwater are crucial aspects of the hydrological cycle. It becomes an essential component for demarcating the boundaries of recharge and discharge areas of any basin. Furthermore, it also helps in identifying the source areas of contamination and pollutants (Olea-Olea et al. 2019; Wang et al. 2015). Therefore, groundwater flow was identified using reduced water levels (RWL). RWL values were determined using elevation data of borehole and water levels between 2010 and 2020. Elevation values were subtracted from water level values of 2010 and 2020 to calculate RWL values.

Results and discussion

Physiochemical analysis distribution of groundwater

In the coastal areas, the chemical composition of groundwater depends on geochemical processes that occur within the aquifer systems, changes are also bound to happen due to coastal seawater intrusion, anthropogenic activities, etc. Table 1 shows physiochemical parameters for the years 2010 and 2020 with calculations of maximum, minimum, mean, variance, and standard deviation. According to the criteria given by WHO and BIS, the maximum desirable limit for TDS is 500 mg/l and the maximum permissible limit is 1000 and 2000 mg/l respectively. The study area showed a maximum value of 10,000 mg/l in Jarpara village, the minimum value was found to be 740 mg/l in Bhorara village with a mean of 2885 mg/l during the year 2010, while during 2020, the study area showed a maximum value of 12,340 mg/l in Jarpara village and a minimum value of 715 mg/l in Bhorara village with a mean of 2766 mg/l (Tables 1 and 3). There are no water samples found within the desirable limit recommended by WHO and BIS for 2010 and 2020. A classification carried out based on Davis and Wiest (1966) for TDS as shown in Table 2 showed that no water samples are within the advisable limit for drinking. Similarly, water samples showed a marked increase in permissible limit from 4.76% in 2010 to 14.28% in 2020. While water type which is useful for irrigation has shown a tremendous amount of reduction from 76.19 to 52.38% from 2010 to 2020, respectively. Moreover, an increase in the category of unfit for drinking and irrigation has shown a rise from 19.04% in 2010 to 33.33% in 2020 (Table 2). Spatial distribution for TDS for 2010 and 2020 (Fig. 2) shows that in 2010, the southwestern and northeastern parts with sampling sites E3, E4, A11, and E1 showed a very high amount of TDS values which ranged from moderately saline to hypersaline zones. However, in 2020 there has been a marked increase in TDS value throughout the study area near the coast (Fig. 2) with an increase in value up to Bhujpar-moti village. Sampling sites E3, E4, A11, E1, E5, D9, B12, and B4 sites showed moderately saline to hypersaline nature, while the rest other locations away from the coastal line showed a good to brackish nature. This analysis tends to suggest that overall, there has been an increase in the amount of salinity near the coast which could be due to an increase in overexploitation leading to seawater intrusion in the coastal aquifers and anthropogenic activity.

pH is an indispensable component to determine water quality. Higher or lower pH values than the desirable limits could be harmful to human health and even to crop production in the agricultural sector. In 2010, pH was in the range of neutral to slight alkaline in nature, while in 2020, pH showed a range from slightly acidic to alkaline nature. Desirable pH according to WHO and BIS ranges from 6.5 to 8.5, while the permissible limit is 6.5–9.5 according to BIS. In the study area in 2010, the maximum and minimum values of pH were found to be 8 and 6.8, respectively, with a mean of 7.39. No samples were found above or below desirable limits. During 2020 maximum and minimum values were 9.05 and 6.2 with a mean of 7.97. 35.09% (8 samples) were found to be above or below the desirable limits, and 64.91% of samples were found within desirable limits as recommended by WHO and BIS. 4.76% (1 sample) sample showed below the permissible limit according to BIS standards (Tables 1 and 3). The mean

Table 1 Analytical results of various hydrochemical parameters in water samples of the study area

S No.	Location code	Village	pre-2010 TDS (mg/l)	pre-2020 TDS (mg/l)	pre-2010 PH	pre-2020 PH	pre-2010 EC (µs/cm)	pre-2020 EC (µs/cm)	pre-2010 Ca^{2+} (mg/l)	pre-2020 Ca^{2+} (mg/l)	pre-2010 Mg^{2+} (mg/l)	pre-2020 Mg^{2+} (mg/l)	pre-2010 TH*
1	A1	Desalpar	1900	1400	6.9	7.1	2968.75	2796	40	56	52.8	54	350
2	B2	Bhujpur Moti	1850	2560	7.3	6.7	2890.625	3690	60	66	19.2	25	400
3	A5	Baraya Nana	1630	2450	7.6	8.62	2546.875	4892	40	23	16.8	22.47	340
4	C1	Bhujpur Moti	1830	2050	7.3	9.05	2859.375	4102	28	26	9.6	10.935	250
5	B4	Samagogha	1860	4650	8	8.43	2906.25	9293	28	34	0	49.82	40
6	E1	Navinal	5600	3590	7.1	6.65	8750	7108	152	148	52.8	48	1330
7	E3	Jarpara	10,000	12,340	6.8	6.93	15,625	16,200	696	735	86.4	92	4300
8	E4	Jarpara	8000	7750	7.1	6.2	12,500	10,820	220	270	72	84	1680
9	C4	Pratappar	1600	2400	7.4	8.75	2500	4794	20	14	0	15.79	130
10	E5	Dhrab	2800	2750	7.4	6.93	4375	3910	20	32	7.2	12	220
11	D6	Kapaya Nana	2600	3560	7.4	8.7	4062.5	7107	48	16	0	29.15	180
12	A6	Pragpar	1830	761	7.8	8.28	2859.375	1516	24	34	12	27.95	200
13	B7	Bhorara	740	715	7.6	8.35	1156.25	1420	20	38	12	37.67	190
14	B6	Kapaya Mota	2400	886	7.4	8.52	3750	1767	24	36	0	23.08	90
15	B8	Bhorara	1630	2000	7.4	8.62	2546.875	4000	36	22	12	21.87	170
16	C8	Mangra	1290	1729	7.3	8.52	2015.625	3452	20	26	0	25.52	70
17	D8	Baroi	1090	1168	7.4	8.78	1703.125	2334	28	24	9.6	14.58	170
18	D9	Goyarsama	1830	4540	7.5	8.17	2859.375	9071	8	82	12	91.13	180
19	A11	Ragha	5500	6860	7.1	8.33	8593.75	13,716	84	68	14.4	99.63	780
20	A9	Gundala	2300	2990	7.9	7.45	3593.75	4240	12	30	12	8	90
21	B12	Luni	2300	2950	7.5	8.3	3593.75	4200	32	40	0	10	100
Maximum			10,000	12,340	8	9.05	15,625	16,200	696	735	86	99.6	4300
Minimum			740	715	6.8	6.2	1156	1420	8	14	0	8	40
Mean			2884.7	3338.0	7.390	7.970	4507.4	5734.6	78.095	86.666	19.085	38.218	536.19
Variance			5,680,176	7,655,620	0.08890	0.74115	1,386,761	1,617,916	22,581.79	25,405.23	619.4743	875.5102	920,474
Standard Deviation			2383.3	2766.8	0.29816	0.86090	3723.9	4022.334	150.2724	159.3902	24.88924	29.58902	959.413

Table 1 (continued)

S No.	Location code	Village	pre-2020 TH*	pre-2010 SO_4^- (mg/l)	pre-2020 SO_4^- (mg/l)	pre-2010 CO_3^- (mg/l)	pre-2020 CO_3^- (mg/l)	pre-2010 HCO_3^- (mg/l)	pre-2020 HCO_3^- (mg/l)	pre-2010 Cl^- (mg/l)	pre-2020 Cl^- (mg/l)	pre-2010 Na^+ (mg/l)	pre-2020 Na^+ (mg/l)	pre-2010 K^+ (mg/l)	pre-2020 K^+ (mg/l)
1	A1	Desalpar	361	307.2	190.13	30	32	488	344	372.225	601	535.61	335	0	0
2	B2	Bhujpur Moti	268	489.6	514	30	60	335.5	515	496.3	540	559.04	696	0	0
3	A5	Baraya Nana	150	364.8	203.69	30	50	518.5	653	496.3	666.46	507.58	711	0	0
4	C1	Bhujpur Moti	110	278.4	193.4	30	60	579.5	670	372.22	553.02	607.05	608	0	0
5	B4	Sama-gogha	290	211.2	409.44	90	110	1006.5	1310	425.40	1566.89	636.23	1435	0	0
6	E1	Navinal	567	1267.2	814	30	60	335.5	397	212.70	1820	1736.5	1008	0	0
7	E3	Jarpara	2215	4118.4	4630	60	82	213.5	338	354.50	433	2627.75	2880	0	0
8	E4	Jarpara	1019.4	1603.2	1773	30	54	396.5	443	283.6	452	2484	2390	0	0
9	C4	Pratap-par	100	211.2	176.94	60	84	671	548	443.12	638.1	552	806	0	0
10	E5	Dhrab	129.2	278.4	303	60	69	427	504	496.3	531	969.45	1077	0	0
11	D6	Kapaya Nana	160	240	166.66	60	72	915	880	478.57	1106	879.17	1160	0	0
12	A6	Pragpar	200	240	45.25	60	30	488	176	638.1	184.34	607.05	197	0	0
13	B7	Bhorara	250	278.4	74.8	60	30	396.5	223	212.7	170.16	219.93	141	0	0
14	B6	Kapaya Mota	185	163.2	51.4	120	22	945.5	145	478.57	241.06	834.90	233	0	0
15	B8	Bhorara	145	249.6	171.52	90	86	640.5	686	443.12	524.66	521.38	651	0	0
16	C8	Mangra	170	172.8	85.42	60	74	671	766	283.6	482.12	440.59	542	0	0
17	D8	Baroi	120	230.4	59.67	30	35	427	346	301.32	311.96	341.11	364	0	0
18	D9	Goyar-sama	580	220.8	145.5	60	90	396.5	470	496.3	1800.86	625.45	1350	0	0
19	A11	Ragha	580	825.6	467.05	60	90	579.5	710	531.75	2623.3	1852.36	2196	0	0
20	A9	Gundala	108	172.8	260	90	60	701.5	790	638.1	570	789.76	1020	0	0
21	B12	Luni	141	172.8	240	90	77	518.5	687	567.2	815	789.76	881	0	0
Maximum			2215	4118	4630	120	110	1007	1310	638	2623.3	2628	2880	0	0
Minimum			100	163	45.25	30	22	214	145	213	170.2	220	141	0	0
Mean			373.74	576	522.612	58.571	63.190	554.80	552.42	429.62	791.94	910.32	984.80	0	0
Variance			230,603	801,801.2	1,031,013	672.8571	566.0619	43,779.34	73,146.76	15,234.5	407,182	455,120	538,322	0	0
Standard Deviation			480.211	895.4	1015.388	25.93949	23.79206	209.2351	270.4566	123.42	638.10	674.626	733.704	0	0

*Total hardness as $CaCO_3$ mg/l

Table 2 Classification of groundwater based on TDS (Davis and De Wiest 1966)

TDS Mg/l	Water type	% of samples	
		2010	2020
< 500	Desirable for drinking	–	–
500–1000	Permissible for drinking	4.76	14.28
< 3000	Useful for irrigation	76.19	52.38
> 3000	Unfit for drinking and irrigation	19.04	33.33

of 7.97 during 2020 shows slight alkaline nature of the water which indicates ingress of brackish water along with these coastal aquifers and use of an excess of fertilizers.

Electrical conductivity (EC) represents the amount enrichment of salt and its concentration within the water. The maximum limit desirable for EC given by WHO is 1500 µs/cm and according to BIS standards maximum permissible limit is 3000 µs/cm. EC ranged from 1156 to 15,625 µs/cm during 2010 with a mean of 4507 µs/cm.

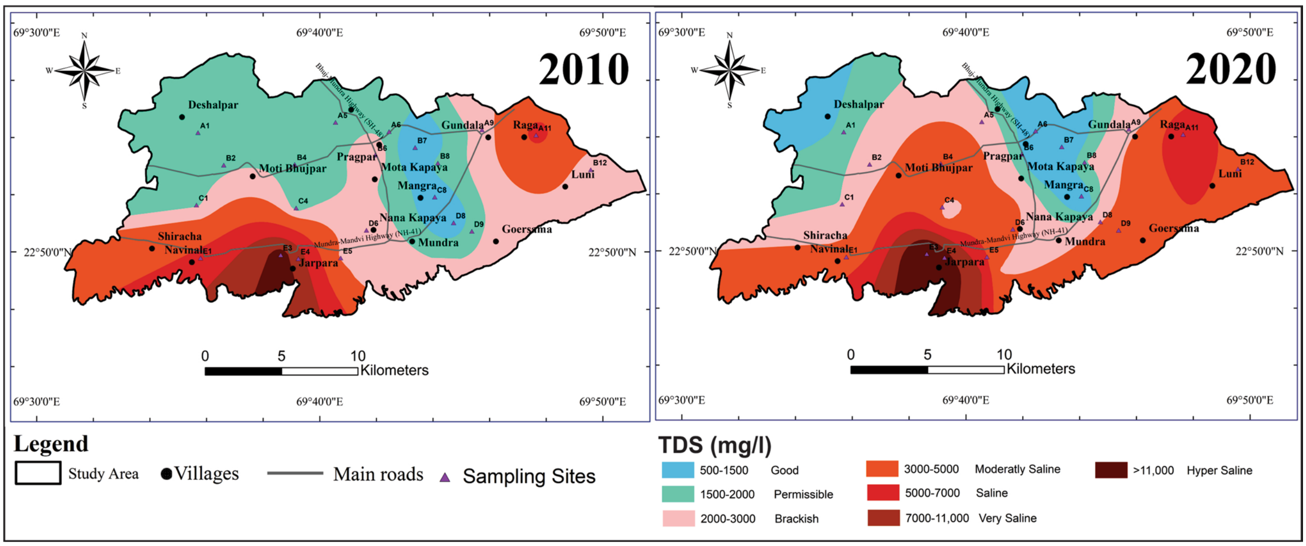

Fig. 2 Geospatial distribution of total dissolved solids (TDS) (Mg/L) of 2010 (Bhimani 2013 and 2020)

Table 3 Statistical analysis of physicochemical parameters of the groundwater samples

Sr No.	Parameters	WHO guidelines (2017)		BIS standards (1998)		Range		Mean-standard deviation (SD)	Mean-standard deviation (SD)
		Desirable limit	permissible limit	Desirable limit	Permissible limit	2010	2020	2010	2020
1	TDS (mg/l)	500	1000	500	2000	740–10,000	715–12,340	2885 ± 2383	3338 ± 2766
2	pH	6.5–8.5		6.5–8.5	6.5–9.5	6.8–8.0	6.2–9.05	7.39 ± 0.298	7.97 ± 0.860
3	EC (µs/cm)	1500	–	–	3000	1156–15,625	1420–16,200	4507 ± 3723	5734 ± 4022
4	Total Hardness ($CaCO_3$) (mg/l)	300	600	300	600	40–4300	100–2215	536 ± 959.41	373.7 ± 480.21
5	Ca^{2+} (mg/l)	75	200	75	200	8–696	14–735	78 ± 150.27	86.7 ± 159.39
6	Mg^{2+} (mg/l)	50	150	30	100	0–86	8–99.6	19 ± 24.89	38.2 ± 29.59
7	Na^{+} (mg/l)	–	200	–	200	220–2628	141–2880	910 ± 674.63	984.8 ± 733.70
8	K^{+} (mg/l)	–	12	–	–	–	–	–	–
9	CO_3^{2-} (mg/l)	–	–	–	–	30–120	22–110	59 ± 25.94	63.2 ± 23.79
10	HCO_3^{-} (mg/l)	–	–	–	–	214–1007	145–1310	555 ± 209.23	552.4 ± 270.46
11	Cl^{-} (mg/l)	200	600	250	1000	213–638	170–2623	430 ± 123.43	791.9 ± 638.11
12	SO_4^{2-} (mg/l)	200	400	200	400	163–4118	45–4630	576 ± 895.43	522.6 ± 1015.39

In 2020, it ranged between 1420 and 16,200 µs/cm. The higher values are found in Jarpara and Ragha villages in 2010, while in 2020 they are found higher in Jarpara, Ragha, Goersama, and Kapaya Nana. Only 4.76% (1 sample) sample during 2020 falls under the desirable limit recommended by WHO in 2010 and 2020. According to BIS standards in total, 57.14% (12 samples) samples were found to be under the maximum permissible limit and 42.86% (9 samples) were found to be saline and unfit for drinking in 2010. In 2020, only 23.80% (5 samples) of water samples are found to be under the maximum permissible limit, and the rest 76.2% (16 samples) of samples were found to be unfit for use in drinking (Tables 1 and 3). The larger mean values during 2010 and 2020 also suggest the higher amount of salt content and salinity within the region, especially along the coast, which are caused by a greater amount of extraction resulting in a higher amount of salts due to ingress of brackish water in the calcareous sandy aquifer near the coast.

Total hardness (TH) is defined as the total concentration of Ca^{2+} and Mg^{2+} in mg/l as $CaCO_3$ which practically implies the amount of resistance that water provides to form frothy soap foams (Saana et al. 2016). Within the study area, total hardness was found in the range of 40–4300 mg/l with a mean of 536 mg/l. In 2020, the range was found to be 100–2215 mg/l having a mean of 373.7 mg/l (Table 1). The maximum desirable and permissible limit provided by BIS is 300–600 mg/l respectively (Table 3). 66.66% of samples (14 samples) showed values within the desirable limit while 33.33% of samples (7 samples) showed values above desirable limits during 2010. Similarly, 80.95% of samples (17 samples) were accounted to be within the permissible limit and 19.04% of samples (4 samples) were above the permissible limit in the 2010 year. In 2020, 71.42% samples (15 samples) were found under the desirable limit and 28.57% samples (6 samples) were observed beyond the desirable limit. 19 samples were found to be within the maximum permissible limit accounting for 90.47% and only 9.52% (2 samples) samples showed results beyond the permissible limit during 2020 as per the recommended BIS standards. Table 4 shows the classification of total hardness based on WHO (2017) showed that 2 samples were found to be soft, 4 samples were medium hard, 8 samples were hard and 7 samples were very hard during 2010, while in 2020, no samples were found in the soft category, 8 samples were medium hard, 7 samples were hard, and 6 samples were found very hard. A higher amount of hardness brings scales on utensils, pipes, water heaters, etc. The use of hard water also leads to many diseases such as cardiovascular, cancer (Durvey et al. 1991), etc. The hardness of water could be due to the presence of alkaline minerals that are present in a higher amount within the lithological units.

Calcium (Ca^{2+}) and magnesium (Mg^{2+}) are the major contributors in increasing the hardness of the water. An increase of calcium and magnesium in water causes scales on utensils, cloths, doesn't allow soap to get dissolved, etc. As shown in Table 3, the desirable and maximum permissible limits as per WHO and BIS standards for calcium are 75–200 mg/l, respectively. In 2010, maximum and minimum values for calcium were 696 and 8 mg/l with a mean of 78 mg/l. In 2020, maximum and minimum values stood at 735 and 14 mg/l with an average value of 86.7 mg/l for calcium. Out of the total samples, 80.95% (17 samples) of the samples were found to be within the desirable limit as per WHO and BIS standards, and the rest 19.04% (4 samples) were observed to be above the desirable limit in 2010 (Tables 1 and 3). However, 90.47% (19 samples) samples were observed under the maximum permissible limit and 9.52% (2 samples) were seen to be beyond the permissible limit in 2010. In 2020, similar kinds of results were observed where 80.95% were within the desirable limit, 19.04% of samples were beyond desirable, 90.47% were within the permissible limit, while the rest 9.52% were beyond the permissible limit. All the samples during 2010 and 2020 were found within the permissible limit (Tables 1 and 3). Magnesium's desirable limit and permissible limit as per WHO are 50 and 150 mg/l, while Indian standard desirable limit and permissible limits are 30 and 100 mg/l. Maximum and minimum values stood at 86 and 0 mg/l with a mean of 19 mg/l during 2010. In 2020, maximum and minimum values were observed to be 99.6 and 8 mg/l, respectively, with a mean of 38.2 mg/l. This analysis shows an almost doubling of mean values in a decade. Although all the samples during 2010 and 2020 fulfilled WHO and BIS standards and were found within the maximum permissible limit. But, according to BIS and WHO desirable limits 80.95% were within the desirable limit and 9.52% were above the desirable limit in 2010. In 2020, slight reduction in percentage was observed where 76.19% and 61.90% samples were within desirable

Table 4 Classification of total hardness (TH) (WHO 2004)

Classification	Hardness range (mg/l)	Range (no. of samples) 2010 (mg/l)	Range (no. of samples) 2020 (mg/l)
Soft	0–75	40–70 (2 samples)	–
Medium hard	75–150	90–130 (4 samples)	100–150 (8 samples)
Hard	150–300	170–250 (8 samples)	160–290 (7 samples)
Very hard	Above 300	340–4300 (7 samples)	361–2215 (6 samples)

limits as per WHO and BIS, respectively, and 23.80% and 38.09% were beyond desirable limits according to WHO and BIS (Tables 1 and 3). The main cause of calcium and magnesium in water is lithological control.

Sulfate (SO_4^{2-}) is a naturally occurring soluble salt within the groundwater systems. Generally, these salts are found inherently within the rock formations rich in clay or gypsum-rich rock formations. Sometimes these are picked up by surficial water and are moved in a dissolved form during the infiltration process resulting in a high number of sulfates within groundwater. As shown in Table 1, the maximum and minimum values found for 2010 were 4118 and 163 mg/l with the mean value being 576 mg/l. In 2020, maximum and minimum values were 4630 and 45.25 mg/l with a mean value of 522.6 mg/l. Only 4 samples accounting for 19.04% were found within desirable drinking water limits, while the rest 80.95% (17 samples) were beyond desirable limits during 2010. But, most of the samples were observed within the permissible limit (76.19%) and only 5 samples (23.80%) were beyond the permissible limit in 2010 as per WHO and BIS standards (Tables 1 and 3), while in 2020 it was found that 52.38% (11 samples) samples were within desirable limits and 47.61% (10 samples) were above desirable limits. 71.42% (15 samples) samples were found within maximum permissible limits, while 28.57% (6 samples) were found beyond permissible limits (Tables 1 and 3). The main cause of sulfate found, appears to be seawater ingression and the presence of clayey formations pockets stretching over a large extent within this sandy aquifer.

Between carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-), the latter was observed to be a dominating ion within the water samples. Carbonate ranged between 30 and 120 mg/l with an average value of 59 mg/l in 2010. In 2020, it ranged from 22 to 110 mg/l with a mean value of 63.2 mg/l. Bicarbonate ion being dominant was found to be in the range of 214–1007 mg/l with a mean value of 555 mg/l during 2010, and during 2020 it ranged between 145 and 1310 mg/l with an average value of 552.4 mg/l (Tables 1 and 3).

Chloride (Cl^-) is major and important ion present within groundwater. Chloride can originate in groundwater with multiple possibilities, which can be anthropogenic or natural. Sources of anthropogenic could be an industrial waste, use of excess fertilizers, and dumping of waste within the subsurface (Appelo and Postma 1996). Natural sources could be the leaching of evaporites and halites, due to the dissolution of salt minerals, and seawater ingression. Desirable limits and permissible limits provided by WHO and BIS are 200, 600, and 250, 1000 mg/l, respectively (Table 3). The study area showed maximum and minimum values of 638 and 213 mg/l, respectively, with a mean value of 430 mg/l during the year 2010 (Tables 1 and 3). In 2020, maximum and minimum values were observed as 2623 and 170.2 mg/l with a mean of 791.9 mg/l. There has been a marked increase in maximum value, mean value, and standard deviation which shows a greater amount of increase in chloride ions (Tables 1 and 3). According to WHO standards, no samples were found within the desirable limit in 2010. Only 9.52% (2 samples) were found beyond the maximum permissible limit and the rest 90.48% samples (19 samples) were observed within the permissible limit during 2010. Similarly, according to BIS 9.52% of samples were within the desirable limit and 90.48% were above the desirable limit in 2010 (Tables 1 and 3). All the samples were within the permissible limit as per BIS standards in 2010. In 2020, as per WHO, 9.52% of samples were under the desirable limit and 90.48% of

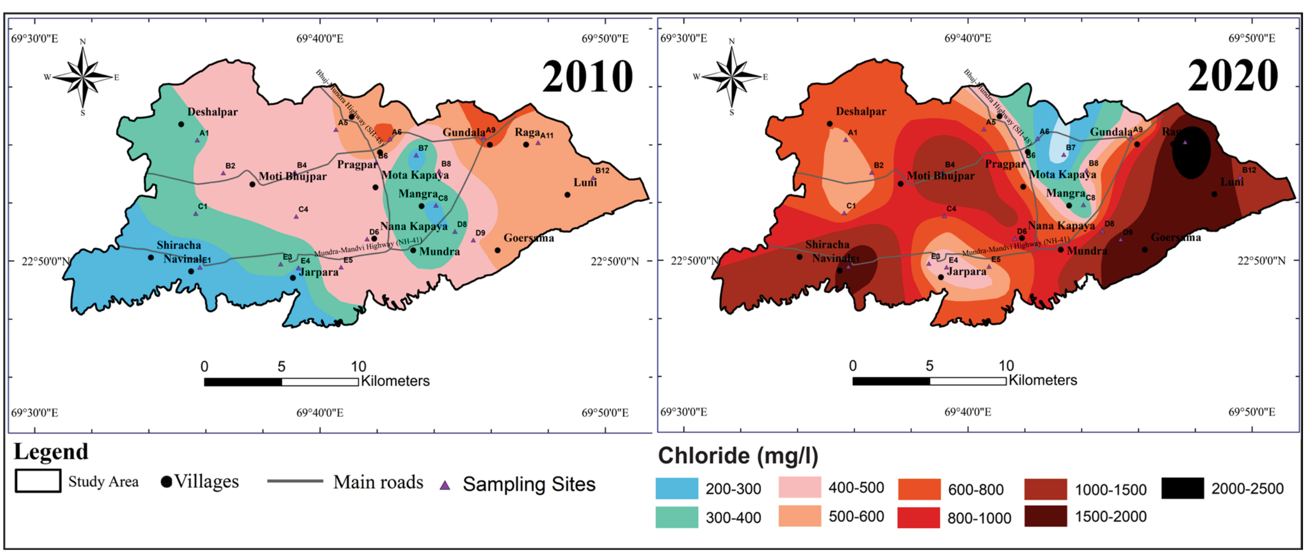

Fig. 3 Geospatial distribution of chloride (Mg/L) of 2010 (Bhimani 2013 and 2020)

samples were beyond a desirable limit. Only 57.14% of samples were found under the maximum permissible limit, while the rest 42.85% were beyond the permissible limit. Only 14.28% samples (3 samples) were found under the desirable limit and the rest 85.71% (18 samples) were beyond the desirable limit in 2020 as per BIS. 76.19% (16 samples) fulfilled BIS standards and were found to be within permissible limits and the rest 23.80% (5 samples) were surpassing the maximum permissible limit in 2020 (Tables 1 and 3). Figure 3 shows spatial distribution values of chloride of 2010 and 2020 which indicates very high concentrated chloride water being present in a study area during 2020. This also indicates that this area is suffering from very high chloride-enriched groundwater in a span of merely a decade. The major cause of high chloride values in a decade is due to overexploitation and over-drafting of groundwater in these coastal areas and the deepening of wells and borewells which are causing seawater to move inland by making it rich in chloride and contaminate the coastal aquifer systems of the surrounding as well.

Sodium (Na^{+}) is one of the most abundant elements on the surface; therefore, it is often found in groundwater systems. The maximum permissible limit recommended by WHO and BIS is 200 mg/l. Higher intake is hazardous which can cause high blood pressure, hypertension, kidney stones, etc. In 2010, all the samples exceeded the maximum permissible limit with maximum and minimum values being 2628 and 220 mg/l. The mean value was 910 mg/l with a standard deviation of 674.63 mg/l (Tables 1 and 3). In 2020, only 2 samples were found within the permissible limit rest of the samples exceeded permissible limits. Analysis showed a maximum value of 2880 mg/l and a minimum value of 141 mg/l with an average value of 984.8 mg/l (Tables 1 and 3). In the study area generally, most of the samples showed much higher values than the permissible limit. The spatial distribution map (Fig. 4) shows much higher values near the coast in 2010 and 2020. Over a decade, sodium values tend to have increased. The area of 1000–1500 mg/l value shows much increase in a decade. The root cause of much higher values is the inherent presence of Na-rich minerals and seawater intrusion at certain locations due to over-drafting and deep drilling.

Potassium (K^{+}) values were found within the WHO standards since it was not detected within the water sample during 2010 and 2020.

Water quality index

The water quality index was evaluated to determine groundwater quality suitability for drinking. The water quality index by the weighted arithmetic method brings complex chemical data into a single value by generating a tally to easily understand the quality conditions in a given area (Boyacioglu 2007). Water quality index values ranged from 39.17 to 341.87 in 2010, while in 2020, it ranged from 64.04 to 327.82 (Table 5). The minimum value was seen in Mangra and near Jarpara village in 2010 and 2020. The maximum value was observed at Jarpara village in 2010 and 2020. The study area showed much more deterioration and higher values of WQI in 2020 as compared to 2010 (Fig. 5). Table 6 shows classification according to Brown et al. (1972) and spatial distribution area of WQI which suggests that good, poor, very poor, and unfit accounted for 1.20, 32.53, 40.46,

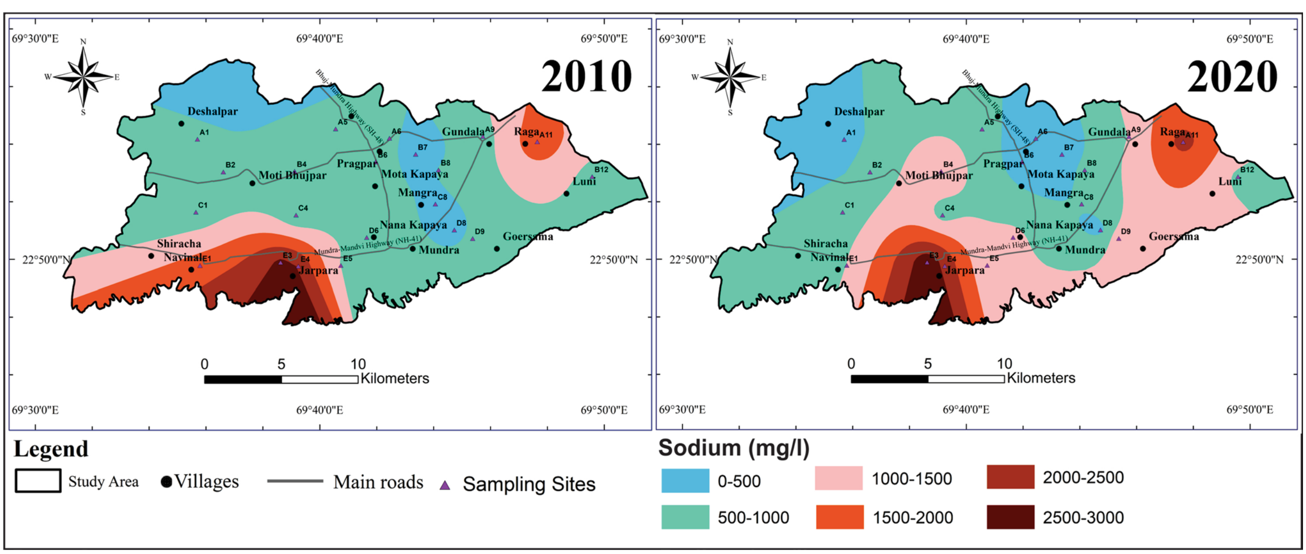

Fig. 4 Geospatial distribution of sodium (Mg/L) of 2010 (Bhimani 2013 and 2020)

Table 5 Analytical results of irrigational quality parameters of the study area

S No.	Location Code	Village	pre-2010 SAR	pre-2020 SAR	pre-2010 KI	pre-2020 KI	pre-2010 RSC	pre-2020 RSC	pre-2010 MH %	pre-2020 MH %	pre-2010 PI %	pre-2020 PI %	pre-2010 Na %	pre-2020 Na %	Pre-2010 WQI	pre-2020 WQI
1	A1	Desalpar	13.02	7.62	3.64	2.00	1.41	0.92	68.75	61.64	87.97	77.47	78.44211	66.61364	77.5	77.0
2	B2	Bhujpur Moti	16.03	18.44	5.28	5.62	1.41	1.94	34.78	38.70	92.20	93.05	84.08649	84.89703	69.1	80.1
3	A5	Baraya Nana	16.93	25.15	6.49	10.23	2.79	4.09	41.18	61.95	98.10	100.73	86.65031	91.09341	74.5	137.5
4	C1	Bhujpur Moti	25.17	25.14	12.00	11.95	4.77	5.87	36.36	41.21	103.09	103.85	92.30601	92.28078	57.5	140.6
5	B4	Sama-gogha	33.06	36.48	19.76	10.66	13.93	4.30	0.00	70.95	109.16	98.22	95.1828	91.42525	80.0	198.0
6	E1	Navinal	30.82	18.36	6.29	3.84	0.54	0.75	36.67	35.09	88.97	83.98	86.28571	79.35758	159.7	146.4
7	E3	Jarpara	24.93	26.57	2.72	2.82	0.13	0.19	17.14	17.26	74.32	75.20	73.12	73.81619	341.9	327.8
8	E4	Jarpara	37.04	32.46	6.35	5.07	0.44	0.44	35.29	34.15	88.44	85.69	86.4	83.52263	221.3	243.8
9	C4	Pratappar	33.94	34.91	24.00	17.38	13.00	5.85	0.00	65.27	109.27	102.65	96	94.56052	50.8	137.8
10	E5	Dhrab	47.13	41.07	26.34	18.01	5.63	4.06	37.50	38.46	102.39	100.56	96.34286	94.73962	76.5	64.0
11	D6	Kapaya Nana	34.89	39.69	15.93	15.62	7.08	5.21	0.00	75.23	103.63	101.06	94.09231	93.98261	70.6	170.1
12	A6	Pragpar	25.17	6.03	12.00	2.13	4.55	0.96	45.45	57.81	102.20	81.50	92.30601	68.00823	81.6	92.7
13	B7	Bhorara	9.56	3.86	4.78	1.22	4.25	0.92	50.00	62.30	104.75	72.00	82.7027	54.88499	50.9	101.1
14	B6	Kapaya Mota	46.86	7.42	30.25	2.72	16.25	0.84	0.00	51.66	107.30	84.25	96.8	73.12404	64.1	102.8
15	B8	Bhorara	19.16	23.41	8.10	9.68	4.82	4.83	35.71	62.36	101.73	101.38	89.00613	90.64107	60.1	128.5
16	C8	Mangra	27.09	18.00	19.16	6.88	13.00	4.38	0.00	62.06	111.49	100.43	95.03876	87.30483	39.2	121.4
17	D8	Baroi	14.14	14.40	6.74	6.55	3.64	2.83	36.36	50.31	102.62	99.82	87.08257	86.76066	47.9	113.1
18	D9	Goyarsama	32.50	24.27	19.42	5.02	6.07	0.92	71.43	64.94	104.02	87.33	95.10383	83.38657	66.0	219.8
19	A11	Ragha	49.01	39.47	14.91	8.16	2.13	1.25	22.22	70.95	97.30	92.26	93.71636	89.08153	125.6	282.2
20	A9	Gundala	38.39	42.61	21.46	20.47	9.06	6.90	62.50	30.77	104.98	103.08	95.54783	95.34195	91.1	79.4
21	B12	Luni	38.39	32.18	21.46	13.52	7.19	4.88	0.00	29.41	103.66	101.27	95.54783	93.11256	68.3	118.3
Maximum			49.01	42.61	30.25	20.47	16.25	6.90	71.43	75.23	111.49	103.85	96.80	95.341	341.9	327.8
Minimum			9.56	3.86	2.72	1.22	0.13	0.19	0.00	17.26	74.32	72.00	73.12	54.884	39.2	64.0
Mean			29.20	24.65	13.67	8.55	5.81	2.97	30.06	51.55	99.88	92.66	90.08	84.19	93.99	146.79
Variance			134.71	149.96	69.23	33.57	22.68	4.74	546.44	269.47	80.32	106.72	42.88	122.53	4957.20	4990.503
Standard Deviation			11.61	12.25	8.32	5.79	4.76	2.18	23.38	16.42	8.96	10.33	6.55	11.07	70.40	70.64

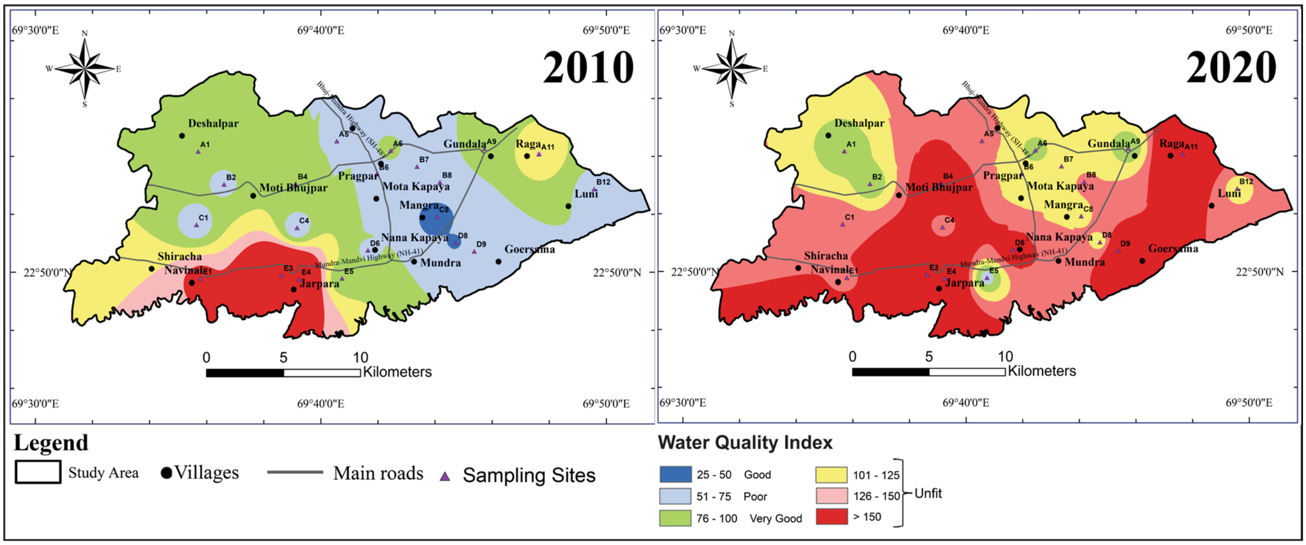

Fig. 5 Water quality index (WQI) maps for the year 2010 and 2020

Table 6 Classification of WQI using weighted arithmetic method (Brown et al. 1972)

WQI RANGE	STATUS	Area % 2010	Area % 2020
0–25	EXCELLENT	–	–
26–50	GOOD	1.20	–
51–75	POOR	32.53	0.140
76–100	VERY POOR	40.46	5.533
> 100	UNFIT FOR DRINKING	25.79	94.326

and 25.79%, respectively, in 2010. 2020 showed 0.40% area under poor, 5.533% area under very poor, and 94.32% under unfit category. Unfit category distribution showed an increase of 68.53% area in 10 years. This suggests that most of the study area's groundwater is unfit and unsuitable for drinking.

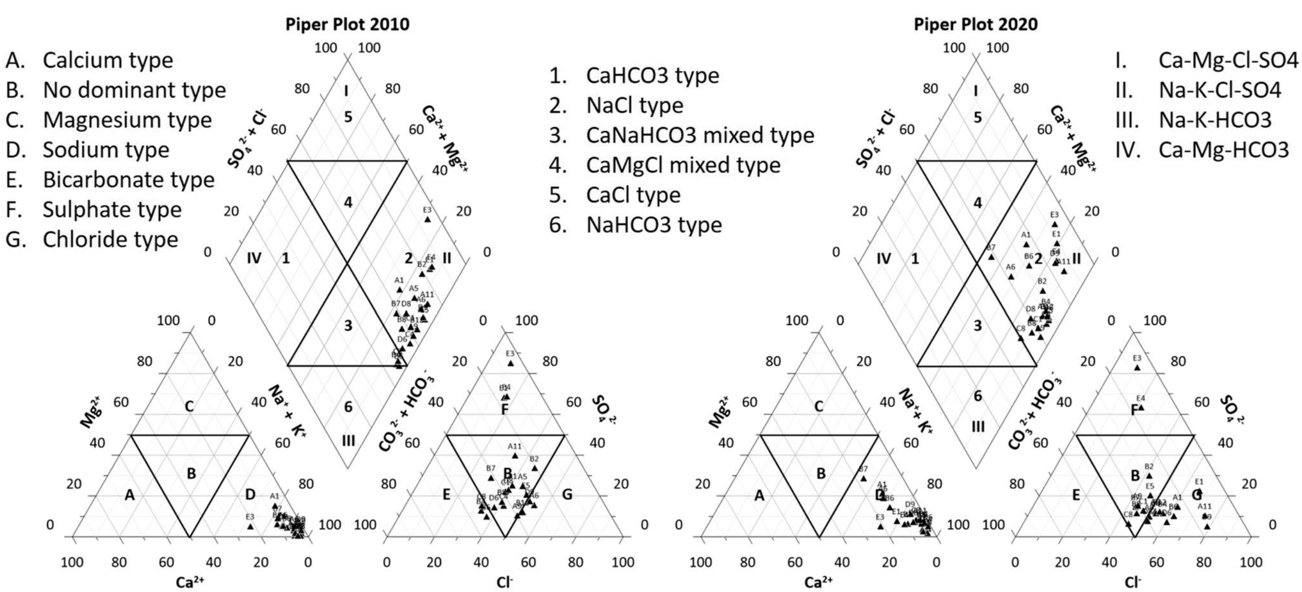

Fig. 6 Piper (1944) plot trilinear plot diagrams showing hydrochemical characteristics of groundwater for 2010 and 2020

Piper trilinear plot

2010 plot showed that all the samples were found to be dominated by sodium and potassium type as cations. Anions showed 57.14% of samples were of no dominant type followed by 14.28% samples of sulfate type, 14.28% samples were bicarbonate type, and 14.28% of chloride type in 2010. 85.71% of samples (18 samples) were dominated by type II (Na^+–K^+–Cl^-–SO_4^{2-}) type of water, while the rest 14.28% of samples (3 samples) showed Ca^{2+}–Na^+–HCO^{3-} type in 2010 (Fig. 6). However, in 2020, 100% of samples represented $Na^+ + K^+$ (D type)-type cations dominant. Anions showed samples being more dominated by Chloride type (G type) accounting for 57.14% (12 samples) followed by 33.33% under no dominant type (B type) and 9.52% (2 samples) showing sulfate type (F type) (Fig. 6). Diamond plot showcased 100% samples being of Na^+–K^+–Cl^-–SO_4^{2-} type (Type II) as shown in Fig. 6. This piper plot of 2010 and 2020 indicated that anions are more dominated by Cl^- ions (57.14%) in 2020 as compared to 2010 which showed only 14.28% samples representing Cl^- ions.

Groundwater suitability for irrigation

Groundwater is an essential element for irrigation purposes. In Kachchh, 75% agriculture sector is fed by groundwater resources (Keesari et al. 2014). As a result, good water quality for irrigation becomes essential as groundwater quality has a direct impact on crop productivity yield, soil permeability, and fertility of the soil. To determine groundwater's suitability for irrigation, electrical conductivity (EC), sodium absorption ratio (SAR), United States Salinity Laboratory (USSL) diagram, residual sodium Carbonate (RSC), Kelly's index (KI), sodium (Na^+) percent, magnesium hazard (MH) and permeability index (PI) were used (Table 5).

Sodium %

Sodium percent values ranged between 73.12 and 96.8 in 2010 and in 2020 it ranged between 54.88 and 95.34% (Table 5). Based on the classification of Wilcox (1955), it was observed that no samples were in an excellent, good and permissible category in 2010. 90.47% samples (19 samples) were seen under the unsuitable category and 9.52% samples (2 samples) were observed under the doubtful category in 2010. In the 2020 year, 71.42% of samples (15 samples) were found unsuitable for irrigation while, 23.80% (5 samples) and 4.76% (1 sample) were under the doubtful and permissible category. Wilcox (1955) plot for sodium percent versus electrical conductivity showed that 71.42% samples (15 samples) were unsuitable for irrigation, 23.80% (5 samples) were doubtful to unsuitable, and 4.76% (1 sample) were found to be under permissible to doubtful during the year 2010 (Fig. 7). A 2020 year showed that 76.19% of samples were completely unsuitable for irrigational use, while each two–two samples were found to be under permissible to doubtful and doubtful to unsuitable categories, respectively.

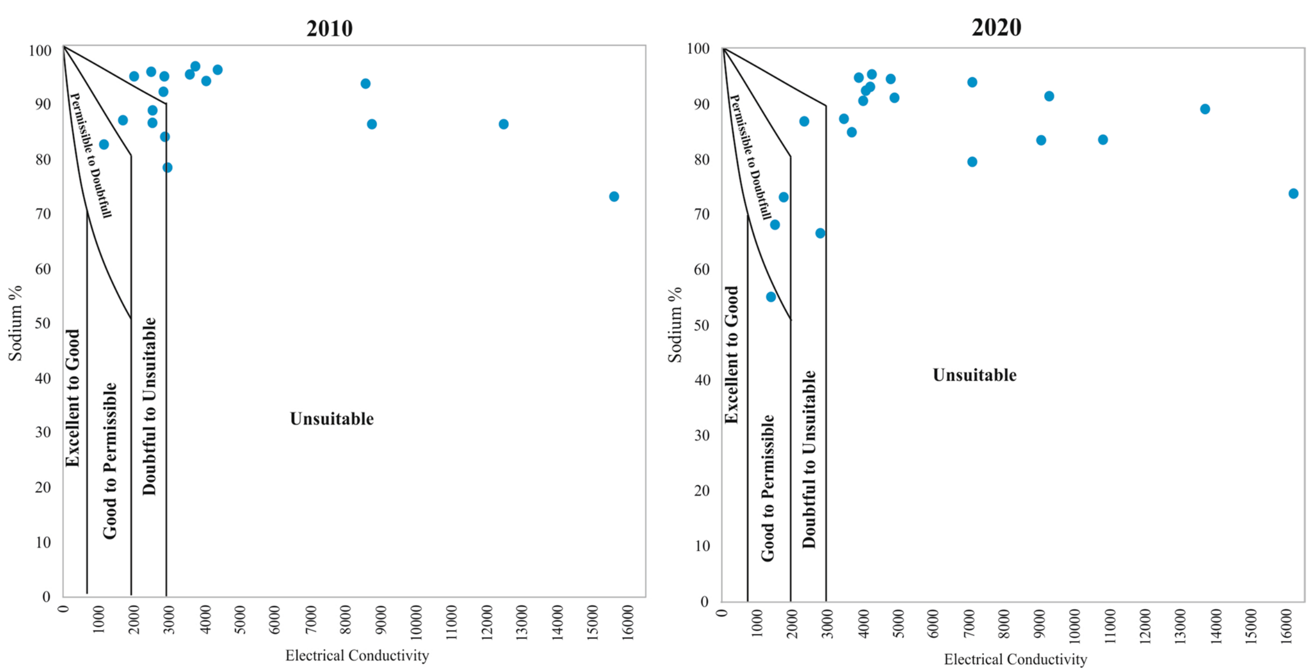

Fig. 7 Wilcox plot diagrams for the classification of groundwater based on electrical conductivity (µs/cm) and sodium % for 2010 and 2020

Only 4.76% (1 sample) was found under the good to permissible category (Fig. 7). More than 85% of samples are found to be doubtful to unsuitable and unsuitable categories. The study area is highly affected by the excess high sodium hazard and high salinity.

Sodium absorption ratio (SAR)

Classification based on SAR values delineates that 57.14% (12 samples) and 19.04% (4 samples) were found under the unsuitable and doubtful category for irrigation in 2010. Only 1 sample and 4 samples were observed to be in the excellent and good category, respectively. In 2020, 52.38% (11 samples) were found doubtful and 19.04% (4 samples) in the unsuitable category. Four samples were identified as excellent and two samples of good category. Overall, there is a higher value of SAR in 2010 and 2020. There has been a reduction in the unsuitable category in 2020 and an increase in percentage in the doubtful category, but still values are much higher which are harmful for irrigation and it requires very good drainage to compensate it. United States Salinity Laboratory (USSL) diagram was taken for checking the suitability for 2010 and 2020. EC versus SAR was plotted, EC was used as salinity hazard, and SAR value was used as alkalinity hazard (Fig. 8). Most of the samples fall under the C4S4 class with 66.66% (14 samples) and 61.90% (13 samples) having very high Sodium and very high salinity between 2010 and 2020 representing very bad quality water. Two samples showed C3S2 having high salinity but medium sodium, 1 sample represented C3S4 having high salinity and very high sodium, 2 samples were observed under C4S3 which had very high salinity and high sodium, and 2 samples showed C4S2 configuration with high salinity and medium sodium during 2010 (Fig. 8). The year 2020 analysis showed 3 samples having C3S1, 3 samples fell under C4S3 configuration, while 1 each sample fell under C4S1 and C4S2, respectively. Most of the samples on average showed high salinity to very high salinity and high sodium which represents that water is of bad to very bad quality as per the USSL chart in the study area.

Residual sodium carbonate (RSC)

In the year 2010, RSC values ranged from 0.13 to 16.25 meq/L (Table 5). RSC values of 2010 suggested that a combined 71.42% of samples accounted for unfit and harmful categories. Results showed that 14.28% samples (3 samples) were safe, 14.28% samples (3 samples) marginal, 28.57% (6 samples) under the unfit category, and 42.85% samples (9 samples) were found under the severely harmful category for plants and human health in 2010. The 2020 year accounted for a total of 52.37% of samples under the unfit to severely harmful category. 38.09% (8 samples) samples were found safe, 9.52% (2 samples) were marginal, 33.33% (7 samples) were unfit, and 19.04% (4 samples) were under the harmful category. Comparison between 2010 and 2020 shows that there has been an increase in the percent of safe water as per RSC values

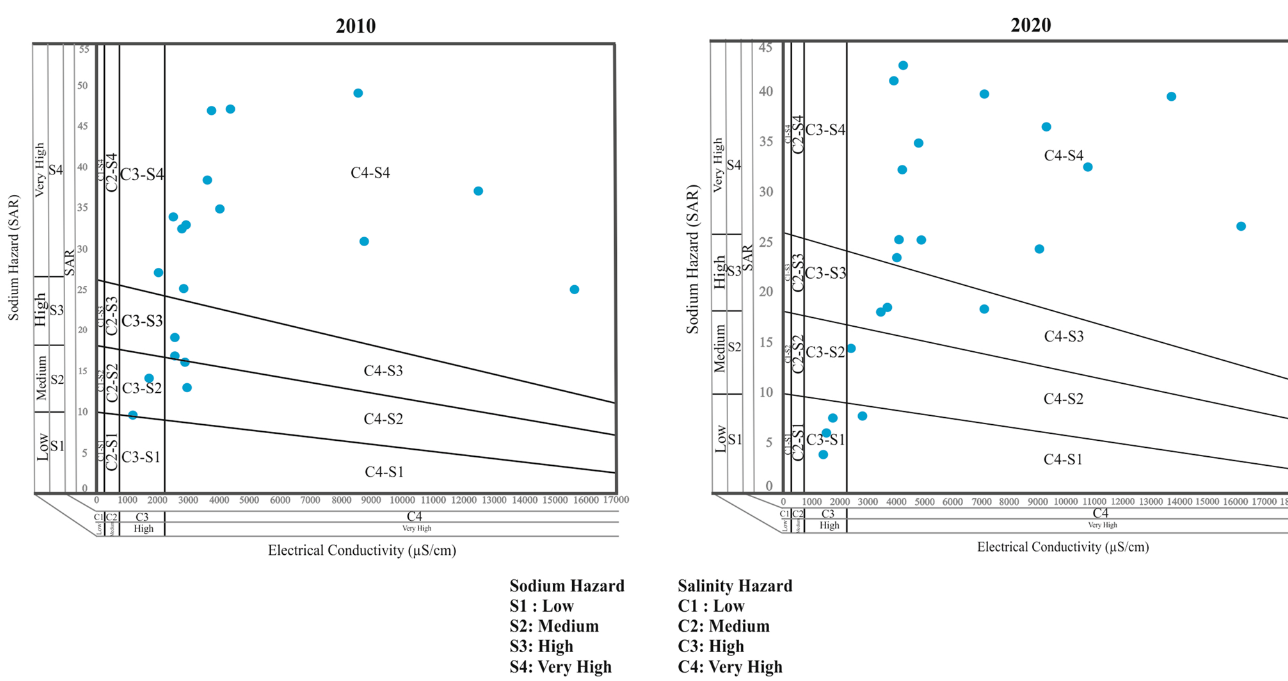

Fig. 8 US salinity diagram (USSL) for classification of irrigation water for the year 2010 and 2020

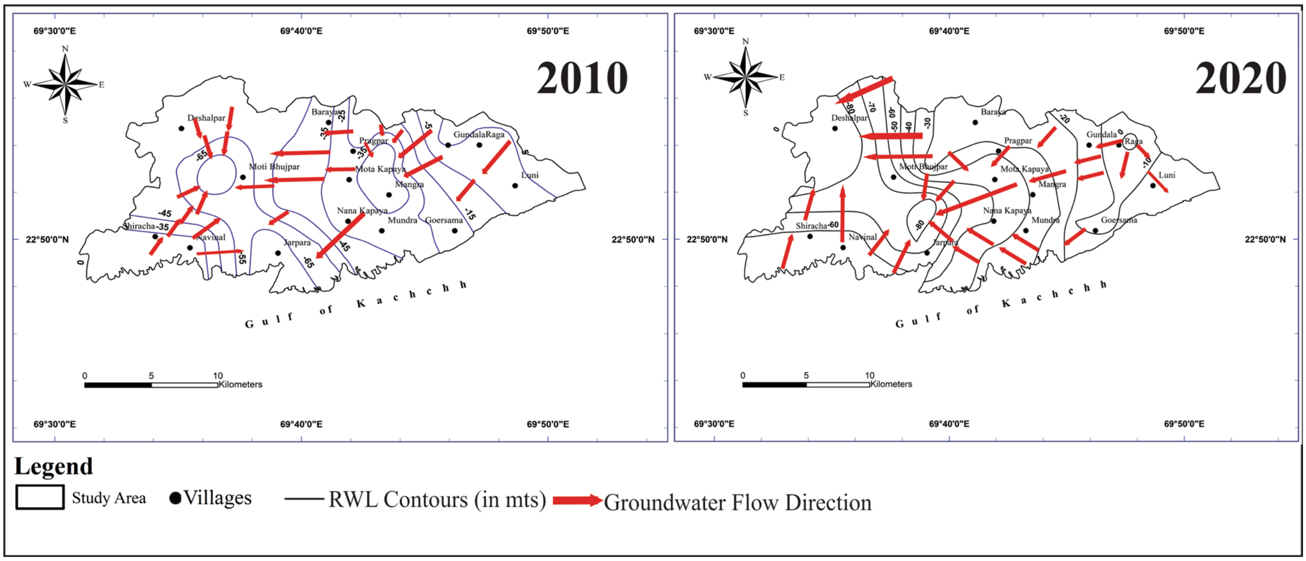

Fig. 9 Reduced water level (RWL) map showing groundwater flow directions for 2010 and 2020

and an increase in the unfit category but a decrease in the severely harmful category during 2020. Higher amount of bicarbonate values as seen in Tables 1 and 5 could be one of the causes of increased sodium values.

Kelly's index

In the year 2010, values ranged between 2.72 and 30.25 meq/L. All the samples observed, showed values greater than 2 making it unacceptable for irrigation in 2010, while in 2020, values ranged from 1.22 to 20.47 meq/L. Two samples were under the negligible category, while the rest 19 samples (90.47%) were completely unacceptable for irrigation in the year 2020. Overall, the study area shows much higher values than safe and negligible ranges.

Magnesium hazard (MH)

MH ranged between 0 and 71.42% in the year 2010 while, ranged between 17.26 and 75.22% in 2020 (Table 5). 14.28% (3 samples) samples were observed under the suitable category, while the rest 85.71% (18 samples) were seen as unsuitable for irrigation. In 2020, 61.90% (13 samples) were under the suitable category and 38.09% (8 samples) were found under the unsuitable category.

Permeability index (PI)

All ion values taken for analysis are in meq/L. Permeability index ranged between 74.31 and 111.49 in 2010 and in 2020, it showed ranges between 72 and 103.85 (Table 5). In the year 2010, 95.23% of samples (20 samples) were under the class-I category representing good permeability, and only 1 sample was observed in the class-II category having suitable PI. No samples were found in the unsafe category in the year 2010. The year 2020 showed similar trends with 90.47% samples showing class-I type having good permeability index and 2 samples showing class-II type having suitable permeability. Similar to 2010, in 2020 no samples were seen under class-III type having unsafe PI.

Groundwater flow, recharge, and discharge evaluation

In the year 2010, Groundwater showed RWL contour values ranging from 5 to − 65 m (Fig. 9). Mostly the subsurface groundwater flow was observed to be towards the southwestern side. Within the study area, subsurface highs and lows are found in groundwater flows. The highs during 2010 were found near Gundala, and Raga village on the east, and Deshalpar on the west which act as recharge zones for groundwater. Subsurface lows were found near Pragpar, Mota-Kapaya, and Mangra where Groundwater accumulation occurs. Reversal of Groundwater flow is observed near Shiracha, Navinal, Jarpara and on the western side of the Moti-Bhujpar village which shows flow toward north-to-northeast direction (Fig. 9). In the year 2020, the RWL values ranged between 0 and − 80 m. Most of the groundwater flows from the southwest to the south direction. Subsurface highs were observed near Gundala and Raga villages where groundwater recharge occurs, and subsurface lows were observed near Pragpar, Mota-Kapaya, Mangra, and Deshalpar Village. Reversal of groundwater flow was observed near Shiracha, Navinal, Jarpara, Nana-Kapaya, Mundra, and south of Deshalpar village in the year 2020 (Fig. 9). Recharge areas occur on the northern ends of the study area, and the discharge areas occur on the southern end of the study area. There has been a marked increment in the area of groundwater reversal flow during 2020 in comparison with 2010. Most of the area showed an increase in the negative values of RWL which represents depleting groundwater levels in the study area in a decade (Fig. 9).

Conclusion

The analysis and understanding of hydrochemical parameters revealed that overall, the water quality has much more deteriorated within one decade. Physiochemical analysis of groundwater showed that TDS values have increased by manifold, and no water samples were found within the desirable limits of drinking given by WHO and BIS standards for the years 2010 and 2020. In 2010, 76.19% of samples were found to be useful for irrigation which reduced to 52.38% in 2020 and 19.04% of samples were found unfit for both drinking and irrigation which rose to 33.33% in 2020. Based on pH, the water showed slight alkaline nature with an average pH value being 7.97 in 2020. No water samples were observed beyond desirable limits in 2010, while 35.09% of samples were observed beyond the desirable limit in 2020. The larger mean values of EC in 2010 and 2020 show a high amount of salinity and salt content. 42.86% of samples were saline and unfit for drinking in 2010 which increased to 76.2% in 2020. According to WHO (2017), 71.42% of samples were found to be hard to very hard in 2010 and it was 61.90% during 2020.19.04% of samples for TH were found to be beyond permissible limit according to BIS in 2010 and it showed only 9.52% during 2020. For the sulfate, 80.95% of samples were beyond desirable and 23.80% were above permissible limits in 2010, and in 2020, 47.61% of samples were found above desirable and 28.57% beyond permissible limit in 2020. The area was found to be dominated by bicarbonate ions during 2010 and 2020. The water samples were also found to be dominated by sodium and chloride ions with a marked increase in mean values of sodium and chloride in the year 2020. In all the samples, sodium exceeded the permissible limit in 2010 and only one sample was found within the permissible limit in 2020 (WHO and BIS). Chloride values were within the permissible limit for all the samples during 2010, while in 2020, 23.80% of samples were marked with very high values of chloride which were much higher values than permissible limits (BIS). Evaluation of WQI suggested that 2010 accounted for 25.79% of the area is unfit for drinking which increased up to 94.32% in 2020. Determination of hydrochemical facies showed that 85.71% of samples were dominated by Na^+–K^+–Cl^-–SO_4^{2-} type and 14.28% were dominated by Ca^{2+}–Na^+–HCO_3^- type during the year 2010. The year 2020 samples showed that all samples are dominated by Na^+–K^+–Cl^-–$SO4^{2-}$ type of water.

Among irrigation suitability, sodium percent represented that all samples were found to be in the doubtful to the unsuitable category for the year 2010. In the year 2020, 95.22% of samples were seen to be under the doubtful to unsuitable category. Wilcox's (1955) plot suggested that more than 85% of samples are under the category of doubtful to unsuitable category during 2010 and 2020 which represents, higher salinity and sodium values in the area. SAR values represented that 76.18% of samples were unsuitable to doubtful in 2010 and 72.42% in 2020. USSL chart also showcased that most of the samples have high to very high salinity and high sodium hazard in 2010 and 2020. Residual sodium carbonate (RSC) values demarcated that 71.42% of samples were under the harmful to unfit category and 14.28% were under the safe category in 2010, while 52.37% of samples were harmful to unfit in 2020 and 38.09% of samples were found to be in a safe category. Kelly's index highlighted the presence of excess sodium, all the samples showed excess sodium, and the values were unacceptable for irrigation in 2010. Similarly, 90.47% of samples were found unacceptable in 2020. Magnesium hazard (MH) values suggested that 85.71% of samples were unsuitable for irrigation in 2010, while the year 2020 showcased 61.90% of samples were unsuitable for irrigation. Most of the samples for the permeability index (PI) showed good permeability for the years 2010 and 2020 which accounted for 95.23 and 90.47%, respectively.

Most values in the study area are above safer limits, making the water very much unacceptable for drinking and irrigation. The prime causes for such conditions in the area during 2020 are:

- Overexploitation of groundwater
- Unconditional deeper drilling in search of fresh water owing to the agricultural activities and industrial growth in the said decade.
- This has led to deepening of groundwater levels, an increase in salinity, and seawater intrusion.

The studies of the RWL values during 2010 and 2020 point out that groundwater flows from subsurface high in the northern recharge zone to the lows in southern coastal regions where groundwater discharges. The studies suggest that the reversal pattern of groundwater flow has increased and it is shifting back to the landward side in 2020 in comparison with 2010. This landward side flow of groundwater in 2020 and increase in the negative values of RWL suggest that groundwater levels are depleting and water column spaces are retrieved, replaced within the subsurface by seawater through the reversal of flow. This is leading to an increase in salinity and seawater intrusion which correlates and matches with RWL flow direction maps and TDS value maps. The use of such water makes the soil infertile, while the saline water infilters back into the aquifer leading to precipitation of excessive minerals into the coastal aquifers making them even more saline. The study area as a part of the arid to the semiarid region is depending more on groundwater for life sustenance which needs microlevel planning of coastal aquifer system recharge and conservation to solve problems of salinity ingress and seawater intrusion.

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Declarations

Conflict of interest The authors declare that they have no competing interests.

Ethical approval The authors confirm that the work has been done according to ethical standards of scientific research.

Ethical conduct The principles of ethical and professional conduct have been followed.

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