



Assessment of groundwater quality for drinking and irrigation purposes in arid areas of Rajasthan, India

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Abstract

The quality of groundwater is poorly understood in the arid northwest part of Rajasthan, whereas it is the only source of drinking and irrigation and the residents consume it without any prior treatment. This study illustrates the qualitative analysis of groundwater and its suitability in the bulk samples collected from three different canal catchment areas. Most of the samples were identified for higher values of EC, TDS, TH and fluoride, therefore considered posing restriction to drinking use. The abundance of major ions was found in the order of $\text{Na}^+ > \text{Ca}^{+2} > \text{Mg}^{+2} > \text{K}^+ = \text{Cl}^- > \text{HCO}_3^- > \text{SO}_4^{2-} > \text{NO}_3^- > \text{F}^-$. The irrigation quality parameters such as sodium adsorption ratio, %Na, residual sodium carbonate, residual sodium bicarbonate, Kelley's index, potential salinity, magnesium hazard, Mg/Ca ratio and permeability index were calculated and discussed thoroughly in combination with Wilcox, USSL and Doneen diagrams. Most of the samples belong to predominant Cl^- and Na^+ in hydrogeochemical studies. According to USSL diagram, majority of the samples fall under C_4S_1 class. Furthermore, groundwater chemistry was found mainly influenced by evaporation–crystallization in Gibbs variation diagram. This study suggested that groundwater is unsafe for drinking purpose without purification and quality measures should be considered while cropping in its irrigation use.

Keywords Groundwater quality · Canal catchment area · Drinking · Irrigation

Introduction

Groundwater is a life-sustaining resource that plays a central part in irrigated agriculture and influences the health of many ecosystems. But unsustainable depletion of groundwater has been documented on both regional and global scales (Rodell et al. 2009; Gleeson et al. 2012; MacDonald et al. 2016). The quality of groundwater is equally important to its quantity owing to the suitability of water for various purposes (Kumar et al. 2009; Subramani et al. 2005). In recent years, intensive agricultural activities, domestic and industrial discharge, over-exploitation, uneven rainfall and mismanagement of groundwater have raised serious concern regarding groundwater contamination (Jain et al. 2010; Salifu et al. 2013; Fianko et al. 2010). The World Health

Organization reports that every year more than 3.4 million people die as a result of water-related diseases and a leading cause of death around the world.

Agriculture is demographically the broadcast economic sector and plays a significant role in the overall socio-economic growth of India. The agriculture growth rate in India GDP has been growing earlier but in the last few years it is constantly declining as 5.0, 1.7, 3.8 and 1.1 in 1996–2000, 2001–2005, 2006–2010 and 2011–2015, respectively. The improvements in irrigation, infrastructure, quality seeds, innovative mechanization, chemical fertilizers and pesticides have helped India to make it seventh largest agricultural exporter worldwide. But, on the other side, massive use of chemical fertilizers and pesticides deteriorated both groundwater quality and soil health (Arumugam and Elangovan 2009; Kurdi et al. 2013; Rajmohan and Elango 2005).

Suitability of groundwater for domestic and irrigation purposes is determined by its groundwater geochemistry because each groundwater system has a unique chemical composition and any alteration depends on several factors such as rock–water interaction, mineral dissolution, soil–water interaction, interaction time, temperature and

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anthropogenic activities (Back and Hanshaw 1965; Drever 1988; Stallard and Edmond 1983; Subba Rao et al. 2002). In order to prevent water-borne diseases, damage to sensitive crops and soil health, groundwater quality measures should be ensured (Sarkar and Hassan 2006; Bauder et al. 2004; Little et al. 2010).

The northwest part of Rajasthan state in India has been selected for the present study. Although three canal systems (Indira Gandhi (IGNP), Bhakra and Gang Canals) are available in the region, an insufficient water supply of canal water and low rainfall made localities depend on the groundwater. Agriculture and livestock are the most common economic activities in the study area; therefore, a hydrogeochemical investigation was carried out to identify groundwater chemistry and its suitability for irrigation and drinking purposes.

Study area

The study area is comprised of northwest part of Rajasthan, located between 28.4°–30.3° north latitude and 72.3°–75.3° east longitude and at an altitude of 175.6 m above mean sea level. To assess groundwater resources and the possibilities of their utilization, this part has been classified under arid climatic region. Rainfall is the main source of annual replenishing groundwater resource which is scanty and mostly up to 0.025 m in the region. The general trend of the slope in the region is from the northeast to southwest. The presence and availability of groundwater vary greatly with changes in topography, subsurface geology and the prevailing climate in the region.

Geology of the region is marked by a thick cover of blown sand and alluvium except for a few isolated patches of recent calcareous and sandy sediments associated with gypsum. The oldest rocks in the area belong to the Aravalli subgroup which includes phyllite, shale and quartz veins. These are overlain by the rocks of upper Vindhyan which are entirely made up of bright to pale red, fine- and medium-grained compact sand stone and silt stone. The windblown sand mainly consists of quartz with minor biotite and magnetite. Gypsum-rich beds are found in shallow depression surrounded by sand dunes. Apart from this, scattered occurrences of saltpeter are seen in number of intradunal basins. The northern part of the area is characterized by arid soils which are light yellowish brown to pale in color. The presence of calcareous concretions has been noticed in the depth range of 75–100 cm. Soils are deep and moderately drained. Permeability is moderate to moderately slow, and water holding capacity and natural fertility are generally poor. Loamy sand and sandy loam are the predominant types of soil met within this soil group. At places, patches of sand also occur. The southern portion of the region is characterized by desert soils, which are very pale brown to yellowish brown in color

and are generally devoid of lime concretions. Soils are generally well drained to excessively drained and have low moisture holding capacity and high permeability. The principal aquifer in the region is alluvium comprising sand, silt, clay and gravel. Groundwater occurs under both water table and confined conditions. The thickness of shallow water table aquifer varies from a few meters to about 80 m. Confined aquifer is found both in alluvium and under lying sandstone and depth ranging from 90 to 100 m.

Porosity, hydraulic conductivity and transmissivity are some important physical concepts to understand the degree to which a body of rock or sediment will function as a groundwater resource. Porosity does not tell the entire story about the availability of groundwater in the subsurface. The pore spaces must also interconnect and be large enough so that water can move through the ground to be extracted from a well or discharged to a water body. The term 'effective porosity' refers to the degree of interconnectedness of pore spaces. For coarse sediments, such as the sand and gravel encountered in alluvial groundwater basins, the effective porosity is often nearly equal to the overall porosity. Specific yield is the fractional amount of water that would drain freely from rocks or sediments due to gravity and describes the portion of the groundwater that could actually be available for extraction. Lower porosity in the soil of study area makes excellent sources of groundwater because of the high specific yield, which allows the groundwater to flow to wells.

Another major property related to understanding water movement in the subsurface is hydraulic conductivity. Hydraulic conductivity is a measure of a rock or sediment's ability to transmit water and often used interchangeably with the term permeability. The size, shape and interconnectedness of pore spaces affect hydraulic conductivity. Hydraulic conductivity is usually expressed in units of length/time: feet/day, meters/day or gallons/day/square foot. Hydraulic conductivity values in rocks range over many orders of magnitude from a low-permeability unfractured crystalline rock at about 10^{-8} feet/day to a highly permeable well-sorted gravel at greater than 10^4 feet/day.

Transmissivity is a measure of the aquifer's ability to transmit groundwater through its entire saturated thickness and relates closely to the potential yield of wells. Transmissivity is defined as the product of the hydraulic conductivity and the saturated thickness of the aquifer. The value of transmissivity in the study area is 375–723 m^2/day .

The agriculture is the main economic venture of this area. Two distinct cropping seasons, namely Kharif and Rabi, can be seen in the study area. Crops grown during the Kharif season include cotton, paddy, moong, guar, jowar, maize and groundnut. Similarly, wheat, gram, mustard, barley, sugar-cane are grown during the Rabi season.

Methodology

A total of 300 groundwater samples were collected from privately owned hand pumps in canal catchment areas of Indira Gandhi (site 1), Bhakra (site 2) and Gang (site 3) during the pre-monsoon season. The geographical position and other details of sampling locations are presented in Fig. 1. Samples were collected after 30 min of pumping and transferred into pre-cleaned polyethylene bottles of 1-L capacity and immediately measured for electrical conductivity (EC), pH and total dissolved solids (TDS) by digital meters. The collected samples were stored in iceboxes after filtration and brought to the laboratory within 24 h and then stored in a freezer at 4 °C for further chemical analysis. Water samples were analyzed for various chemical constituents using standard methods prescribed by the American Public Health Association (APHA 1989, 1995). Calcium (Ca⁺²), magnesium (Mg⁺²) were determined by titrimetric method and

sodium (Na⁺), potassium (K⁺) by flame photometrically. Chloride (Cl⁻) and bicarbonate (HCO₃⁻) were analyzed titrimetrically, whereas fluoride (F⁻), nitrate (NO₃⁻) and sulfate (SO₄⁻²) were determined by spectrophotometric techniques.

Various irrigation water quality parameters such as total hardness (TH), sodium adsorption ratio (SAR), percent sodium (%Na), residual sodium carbonate (RSC), residual sodium bicarbonate (RSBC), magnesium hazard (MH), Mg/Ca ratio, Kelley’s index (KI), permeability index (PI) and potential salinity (PS) were calculated using physicochemical analyses (Todd 1980; Hem 1985).

Total Hardness is calculated by the formula—TH

$$= 2.497 Ca^{+2} + 4.115 Mg^{+2}$$

The correlation of analytical data and classification for suitability were assessed by plotting different graphical representations like Piper (1944), Wilcox (1955), USSL (1954),

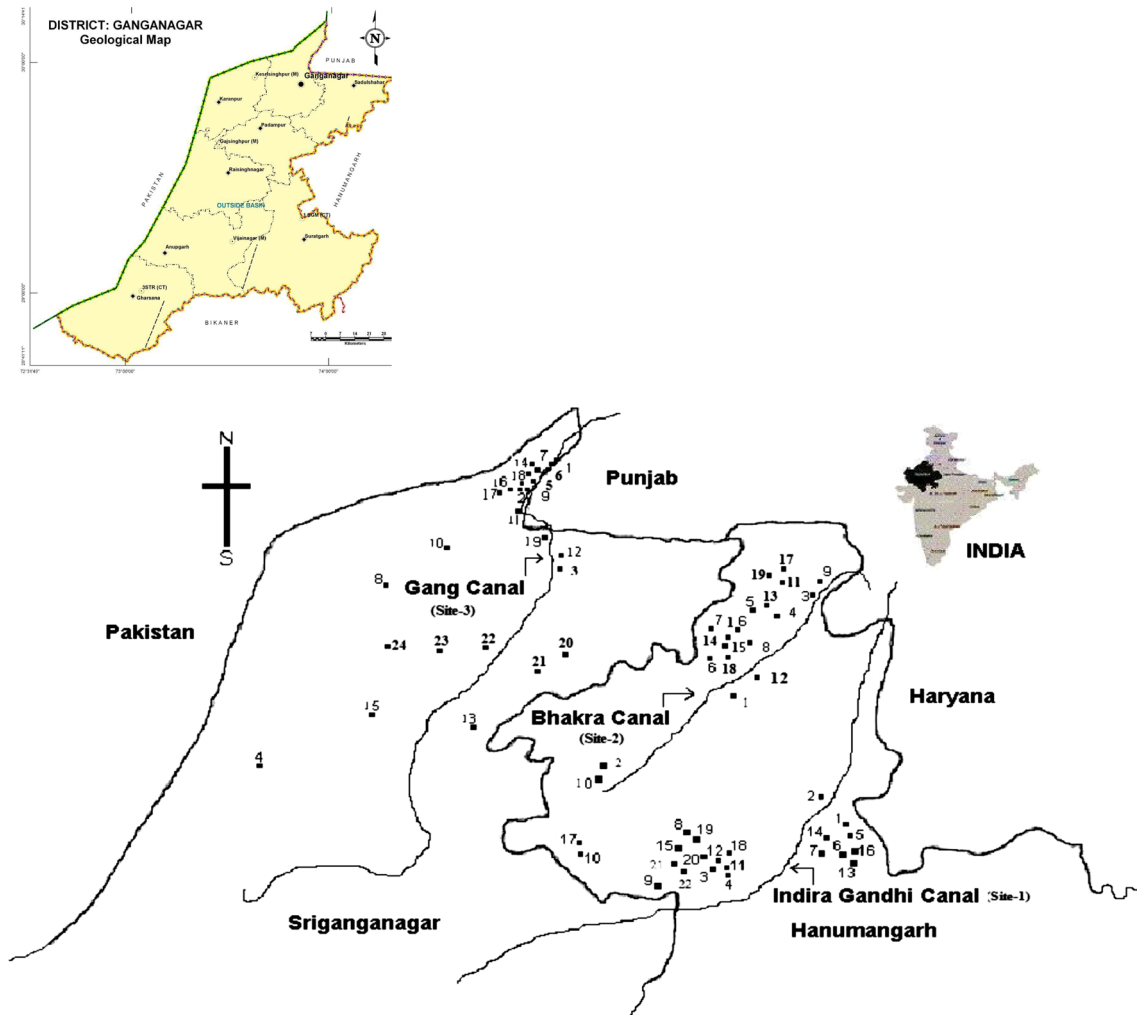


Fig. 1 Location of groundwater sampling in three different sites

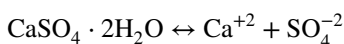
Gibbs (1970), Doneen (1964a) using Arc-GIS-9.3 and rockworks 16 software.

Result and discussion

Quantitative analyses of different physicochemical parameters are the prime factors to determine the quality of water. Analytical data for the various parameters are given in Tables 1, 2 and 3 for three different sites. To ascertain the suitability of collected groundwater samples for drinking and irrigation purposes was discussed separately on comparison with recommended standard values.

Drinking suitability

The adequacy of groundwater for domestic use is directly related to different physicochemical parameters and their concentrations. The mean values of different physicochemical parameters for three canal catchment areas are presented in Tables 1, 2 and 3. The pH of groundwater of all samples ranged between 7.0 and 9.62, which looks slightly higher than the limit described by WHO (6.5–8.5) (WHO 2011). The maximum pH value (9.62 ± 0.27) was observed in the Paliwal-12 STB in Indira Gandhi Canal catchment area. All the water samples were designated to be neutral to alkaline in nature. Dissolution of gypsum present in aquifer rock is responsible for higher salinity.



The electrical conductivity (EC) of groundwater was in the range of 310–17,900 $\mu\text{S}/\text{cm}$. Most of the samples exceed the permissible level (3000 $\mu\text{S}/\text{cm}$ BIS 2003) of EC. The sample collected from 56 LNP showed maximum EC ($17,900 \pm 5630$) which directly indicates the presence of higher levels of cations and anions. The TDS values were remarkably higher and ranged between 219.88 and 6897.29 mg/l (56 LNP, Gang catchment). The samples collected from Gang Canal catchment had comparatively higher values of TDS which directly indicate the presence of high concentration of soluble salts and make water unsuitable for drinking (Hem 1985). The excess TDS in groundwater enriches the soil salinity and also affects the physical properties and fertility of soil (Table 4).

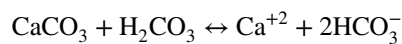
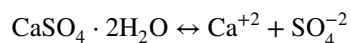
Davis and De Wiest (1966) classified the water samples under different TDS conditions. In the study, most of water samples belong to hazardous level of TDS for domestic use of groundwater (Table 5).

Total hardness (TH) of groundwater in this area was in the range of 35–4210 mg/l, and maximum reported sample was from 56 LNP in Gang Canal catchment.

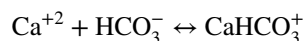
The groundwater study for total hardness (TH) shows that the majority of the samples fall under the hard water category (Table 6).

The hardness of water is due to the presence of alkaline earths such as calcium and magnesium and exists in bicarbonate forms.

The Mg^{+2} and Ca^{+2} are important factors of water hardness, and their presence remarkably influences the chemistry of groundwater. The Mg^{+2} concentration varied from 6.0 to 692.4 mg/l (maximum in 56 LNP, Gang catchment), and Ca^{+2} ranged from 2.0 to 530 mg/l (maximum in Jaloki village in Gang catchment). The presence of Mg^{+2} and Ca^{+2} in the study area is mainly geogenic in origin as the aquifer of this region is composed of rocks rich in limestone, dolomite and gypsum which contain considerable amount of Mg^{+2} and Ca^{+2} . Most sampling sites showed remarkable two- to threefold higher concentration of Mg^{+2} and Ca^{+2} in groundwater than the safe limit by WHO. Dissolution of gypsum and weathering reactions are responsible for Ca^{+2} enrichment in groundwater in the region as these minerals found in aquifer rocks.



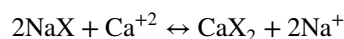
Further instantaneous complexing reactions occur.



The solubility of Ca carbonate is increased by the formation of the aqueous Ca bicarbonate complex.

Several epidemiological investigations have demonstrated the relation between risk of cardiovascular disease, growth retardation, reproductive failure and other health problems and hardness of drinking water (Sengupta 2013).

The range of Na^{+} and K^{+} in the area varied from 11.5 to 1009.7 mg/l and 1.56 to 95.94 mg/l, respectively. Eighty percent of samples collected from Bhakra Canal catchment were exceeding the permissible limit of BIS 200 mg/l Na^{+} , and maximum was reported in Bolanwali village in Bhakra catchment, whereas groundwater samples in Gang catchment were reported with higher levels of K^{+} with maximum in 56 LNP. Although Na^{+} and K^{+} are naturally occurring ions in groundwater, domestic and industrial wastes are other contributors of these (Garg et al. 2009). Cation exchange reaction between Ca^{+2} and Na^{+} also occurs naturally in the groundwater.



The relationship between elevated sodium intake and hypertension has been the subject of considerable scientific controversy. Excessive salt intake seriously aggravates chronic congestive heart failure, and ill effects due to high

Table 1 Analytical results (mean values) of groundwater samples in Indira Gandhi Canal catchment area (site 1)

Sample ID	No. of samples	Turbidity (NTU)	pH	EC (µS/cm)	TDS (mg/l)	TH (mg/l)	Ca (mg/l)	Mg (mg/l)
IGC1	5	2.54	8.05 (0.12)	1630 (221)	656.28 (12.8)	383 (76.4)	55.6 (5.9)	58.56 (5.6)
IGC2	6	2.65	7.79 (0.23)	2490 (243)	1423.37 (304.1)	1153 (43.9)	158.4 (12.8)	181.56 (17.8)
IGC3	4	0.55	7.79 (0.07)	2490 (345)	1076.91 (211.7)	849 (32.9)	123.6 (8.9)	129.6 (23.7)
IGC4	11	1.40	7.66 (0.09)	2840 (543)	1117.80 (226.8)	694 (78.8)	98.6 (7.9)	107.28 (11.2)
IGC5	7	3.93	8.40 (0.12)	2040 (256)	1650.57 (554.0)	291 (43.2)	50.8 (4.7)	39.24 (4.5)
IGC6	6	3.20	8.16 (0.23)	2110 (265)	1073.32 (32.9)	297 (22.4)	48 (10.2)	42.36 (3.2)
IGC7	5	1.86	7.74 (0.14)	3510 (231)	1517.72 (508.9)	865 (32.2)	118.4 (16.8)	136.56 (23.5)
IGC8	2	1.90	7.90 (0.06)	1370 (435)	658.84 (34.7)	380 (32.8)	68 (8.9)	50.4 (8.7)
IGC9	3	4.40	7.70 (0.32)	2630 (658)	1033.33 (65.6)	572 (22.1)	85.4 (7.6)	86.04 (7.8)
IGC10	3	1.00	8.86 (0.11)	1450 (112)	697.32 (54.9)	385 (44.8)	28.6 (4.6)	44.76 (7.1)
IGC11	7	3.26	7.63 (0.10)	3250 (332)	1359.02 (112.9)	1287 (112)	198.2 (32.1)	189.72 (28.7)
IGC12	4	2.95	7.69 (0.04)	1990 (521)	884.11 (45.7)	854 (56.9)	168.6 (18.2)	103.8 (32.4)
IGC13	5	2.86	7.66 (0.02)	3480 (332)	1467.04 (77.8)	1020 (67.9)	158.4 (22.1)	149.76 (23.3)
IGC14	2	1.25	7.95 (0.07)	1370 (554)	567.05 (67.6)	405 (81.0)	54 (8.9)	64.8 (4.5)
IGC15	3	4.83	7.80 (0.32)	2340 (461)	979.43 (34.9)	853 (34.6)	134.6 (21.2)	123.96 (36.7)
IGC16	6	2.25	7.74 (0.22)	2290 (428)	1627.71 (66.5)	1148 (56.6)	173.4 (10.9)	171.36 (45.7)
IGC17	5	1.96	7.60 (0.15)	3320 (321)	1395.08 (69.6)	825 (78.5)	125.2 (8.7)	122.88 (34.4)
IGC18	5	1.36	7.55 (0.02)	4940 (673)	2051.23 (341.6)	1345 (34.8)	196 (54.1)	205.2 (32.6)
IGC19	2	0.75	7.75 (0.09)	2430 (323)	1044.99 (76.6)	550 (44.5)	95 (4.8)	75 (12.7)
IGC20	6	1.70	8.25 (0.07)	610 (554)	334.36 (41.0)	178 (66.7)	18 (2.3)	31.8 (6.9)
IGC21	2	1.90	7.30 (0.16)	4000 (448)	1725.78 (104.8)	1253 (77.8)	222 (76.9)	167.4 (55.3)
IGC22	2	1.70	7.40 (0.32)	3800 (221)	1724.27 (102.7)	1300 (110.9)	218 (78.8)	181.2 (32.1)
Sample ID	No. of samples	Na (mg/l)	K (mg/l)	F (mg/l)	Cl (mg/l)	HCO ₃ (mg/l)	NO ₃ (mg/l)	SO ₄ (mg/l)
IGC1	5	96.6 (8.9)	10.14 (3.4)	4.40 (2.3)	162.59 (43.6)	378.2 (17.8)	25.08 (6.7)	56.16 (10.8)
IGC2	6	207.92 (12.3)	18.33 (6.7)	4.58 (2.1)	511.91 (43.2)	477.63 (23.8)	25.59 (7.6)	78.72 (6.8)
IGC3	4	119.6 (14.5)	15.99 (5.4)	5.0 (0.6)	348.965 (22.5)	411.75 (16.9)	23.26 (4.9)	108.96 (21.5)
IGC4	11	244.49 (54.2)	16.77 (10.6)	3.81 (0.8)	353.225 (33.3)	427 (31.8)	25.56 (5.9)	70.08 (7.8)
IGC5	7	260.59 (23.7)	6.63 (9.8)	3.50 (0.6)	223.65 (43.1)	610 (76.7)	33.03 (4.5)	51.36 (6.5)
IGC6	6	284.97 (45.5)	6.63 (6.7)	3.08 (1.2)	354.29 (22.8)	447.13 (65.5)	35.32 (6.7)	39.36 (5.6)
IGC7	5	273.01 (54.8)	19.11 (6.8)	3.20 (2.1)	646.81 (34.8)	463.6 (8.9)	19.24 (6.6)	71.52 (7.8)
IGC8	2	91.54 (43.7)	8.58 (2.7)	2.50 (0.9)	136.675 (21.8)	427 (43.3)	21.80 (3.5)	68.16 (10.4)
IGC9	3	177.79 (32.9)	16.38 (3.5)	3.17 (0.5)	308.85 (56.6)	589.87 (56.6)	19.67 (6.5)	43.2 (8.3)
IGC10	3	120.06 (34.2)	17.94 (4.5)	2.50 (0.3)	169.335 (23.2)	406.87 (12.9)	17.50 (7.8)	15.36 (7.5)
IGC11	7	158.24 (22.1)	16.38 (7.6)	2.79 (0.4)	489.545 (33.6)	383.69 (15.7)	17.48 (4.5)	95.04 (13.5)
IGC12	4	48.53 (23.4)	10.53 (5.2)	2.75 (0.5)	304.59 (43.2)	320.25 (21.7)	10.63 (7.5)	76.32 (10.2)
IGC13	5	243.8 (35.5)	15.21 (4.4)	2.80 (0.3)	614.15 (54.2)	378.2 (54.8)	26.86 (10.4)	68.16 (8.7)
IGC14	2	74.29 (31.8)	8.97 (5.7)	5.25 (0.4)	86.975 (22.8)	366 (65.6)	23.25 (6.8)	71.04 (5.2)
IGC15	3	113.62 (32.6)	10.92 (7.2)	3.50 (0.6)	307.785 (43.8)	386.13 (34.6)	13.79 (8.5)	80.16 (14.5)
IGC16	6	317.63 (22.8)	16.77 (6.9)	3.17 (0.4)	561.61 (25.5)	427 (76.6)	25.23 (6.6)	133.92 (32.1)
IGC17	5	252.31 (45.6)	10.92 (8.2)	2.60 (0.6)	541.73 (43.2)	414.8 (43.3)	30.23 (7.8)	102.72 (11.6)
IGC18	5	386.4 (43.8)	17.94 (5.9)	3.90 (0.5)	803.72 (56.6)	512.4 (21.3)	20.36 (5.6)	163.2 (12.5)
IGC19	2	178.71 (45.7)	11.7 (5.7)	2.75 (0.2)	397.6 (22.7)	427 (56.8)	23.28 (4.9)	49.44 (5.7)
IGC20	6	47.15 (7.8)	9.36 (3.5)	1.92 (0.7)	72.065 (8.7)	203.13 (21.5)	20.30 (7.8)	11.04 (8.5)
IGC21	2	192.74 (19.5)	12.48 (2.2)	4.50 (0.5)	704.675 (18.9)	488 (48.8)	24.40 (9.5)	156.48 (4.6)
IGC22	2	155.25 (43.3)	12.87 (3.2)	2.50 (0.5)	392.275 (34.8)	488 (34.9)	25.20 (4.8)	140.16 (23.8)

Table 2 Analytical results (mean values) of groundwater samples in Bhakra Canal catchment area (site 2)

Sample ID	No. of samples	Turbidity (NTU)	pH	EC ($\mu\text{S}/\text{cm}$)	TDS (mg/l)	TH (mg/l)	Ca (mg/l)	Mg (mg/l)
BC1	8	2.03	8.01 (1.45)	2220 (443)	946.44 (34.2)	655 (34.8)	61.2 (3.5)	120.48 (32.8)
BC2	7	5.40	7.63 (2.23)	3870 (456)	1661.91 (156.2)	684.29 (56.9)	112.6 (4.8)	96.72 (5.4)
BC3	2	2.0	7.84 (0.87)	8050 (832)	2770.66 (234.0)	1525 (234)	238 (23.7)	223.2 (32.7)
BC4	8	6.83	7.92 (0.56)	5400 (435)	2185.11 (78.8)	1051.25 (78.9)	170.2 (34.4)	150.12 (6.7)
BC5	8	4.03	7.86 (0.76)	4500 (675)	1988.05 (242)	844.38 (23.8)	139.6 (12.7)	118.92 (15.6)
BC6	3	0.97	8.55 (1.20)	3070 (342)	1494.57 (554)	450 (45.9)	63.4 (6.5)	69.96 (7.8)
BC7	3	5.60	8.37 (0.05)	1940 (128)	957.01 (45.9)	275 (34.5)	47.4 (2.8)	37.56 (8.4)
BC8	5	2.52	7.39 (0.32)	4190 (654)	1718.95 (98.7)	1122 (198)	175.6 (34.7)	163.92 (10.6)
BC9	6	1.58	7.42 (0.45)	3690 (823)	1650.37 (38.8)	946.67 (82.9)	168.4 (33.5)	126.24 (12.3)
BC10	6	1.22	8.17 (0.87)	6280 (467)	2560.47 (165)	1154 (231)	145.6 (22.1)	189.6 (10.3)
BC11	2	1.0	8.51 (0.34)	4550 (342)	2061.04 (210)	1103 (59.9)	182 (38.8)	155.4 (7.7)
BC12	5	1.20	7.88 (0.78)	7620 (321)	2922.35 (154)	2064 (178)	197.2 (56.6)	377.04 (14.5)
BC13	2	4.60	7.46 (0.34)	6350 (228)	2695.88 (235)	1313 (58.9)	100 (34.8)	255 (12.6)
BC14	4	1.80	7.89 (0.65)	4380 (765)	1898.40 (345)	936.25 (45.6)	128.6 (12.4)	147.6 (16.8)
BC15	7	3.87	7.98 (0.87)	5490 (389)	2229.89 (231)	1246 (342)	184.2 (34.2)	188.52 (23.7)
BC16	2	8.35	7.48 (0.22)	6650 (548)	2596.20 (174)	1133 (278)	182 (56.2)	162.6 (21.4)
BC17	15	3.46	7.80 (1.78)	3920 (387)	1783.14 (78.9)	804.67 (56.3)	138.2 (16.7)	110.16 (24.8)
BC18	4	9.68	8.0 (0.45)	2120 (389)	966.89 (56.7)	433.75 (23.8)	74 (7.8)	59.76 (5.7)
BC19	3	1.57	8.06 (0.34)	3290 (438)	1408.81 (145)	595 (38.9)	99.4 (5.9)	83.16 (6.7)
Sample ID	No. of samples	Na (mg/l)	K (mg/l)	F (mg/l)	Cl (mg/l)	HCO ₃ (mg/l)	NO ₃ (mg/l)	SO ₄ (mg/l)
BC1	8	185.38 (23.4)	12.87 (5.6)	1.69 (0.6)	206.965 (45.8)	411.75 (23.8)	7.06 (0.6)	115.2 (23.2)
BC2	7	423.66 (22.8)	11.31 (3.4)	4.36 (0.7)	621.605 (36.8)	496.54 (24.5)	10.15 (0.5)	138.72 (13.7)
BC3	2	817.19 (45.5)	19.89 (6.5)	5.75 (0.5)	1031.275 (76.6)	518.5 (33.8)	5.72 (0.7)	174.24 (24.5)
BC4	8	558.9 (34.4)	11.7 (4.5)	2.38 (1.0)	878.625 (56.6)	488 (56.6)	12.31 (1.7)	157.92 (32.7)
BC5	8	515.43 (43.3)	11.7 (4.8)	4.31 (0.9)	796.62 (78.8)	465.43 (37.7)	9.83 (1.5)	147.84 (14.5)
BC6	3	465.98 (54.4)	8.97 (2.3)	3.67 (0.5)	488.835 (45.9)	528.87 (26.6)	11.13 (1.9)	146.4 (6.9)
BC7	3	275.77 (23.3)	9.75 (3.7)	1.50 (0.6)	185.665 (23.8)	528.87 (45.5)	11.44 (0.9)	64.8 (5.9)
BC8	5	326.14 (62.7)	18.72 (2.5)	1.90 (0.4)	587.88 (56.6)	585.6 (42.2)	10.64 (0.7)	141.6 (10.8)
BC9	6	306.13 (75.5)	9.75 (3.2)	1.0 (0.5)	565.16 (45.5)	599.63 (12.8)	14.84 (0.7)	158.88 (7.6)
BC10	6	727.26 (45.5)	18.72 (3.0)	3.0 (0.9)	1021.69 (33.6)	477.63 (43.9)	19.43 (0.8)	157.92 (10.5)
BC11	2	540.96 (76.6)	15.6 (2.4)	2.75 (0.5)	793.425 (23.8)	335.5 (23.3)	3.53 (0.3)	141.12 (9.8)
BC12	5	661.71 (34.8)	24.18 (4.6)	3.20 (0.8)	1249.6 (45.5)	463.6 (45.8)	11.09 (2.8)	166.08 (32.6)
BC13	2	694.83 (47.8)	17.55 (3.8)	2.75 (0.6)	1221.2 (43.1)	427 (37.8)	14.12 (0.8)	177.6 (12.0)
BC14	4	516.81 (23.3)	14.43 (5.6)	3.38 (0.5)	684.44 (65.7)	457.5 (45.5)	4.98 (1.2)	156.48 (21.7)
BC15	7	507.15 (34.2)	18.33 (4.2)	3.0 (0.7)	928.68 (33.2)	427 (67.7)	22.19 (6.8)	148.32 (21.5)
BC16	2	720.13 (62.8)	16.77 (2.3)	2.75 (0.5)	1128.9 (123.8)	396.5 (34.8)	4.88 (0.6)	181.92 (11.5)
BC17	15	446.2 (66.7)	11.31 (7.2)	3.13 (0.6)	663.495 (32.8)	483.73 (34.8)	13.85 (4.7)	153.6 (12.3)
BC18	4	243.34 (34.5)	9.36 (2.4)	3.63 (0.9)	295.715 (57.7)	381.25 (23.9)	12.00 (3.8)	82.08 (4.9)
BC19	3	368.46 (54.2)	7.8 (3.1)	4.50 (0.7)	383.4 (42.1)	589.87 (32.2)	11.51 (7.8)	139.2 (7.2)

levels of sodium in drinking water have been documented. Infants with severe gastrointestinal infections can suffer from fluid loss, leading to dehydration and raised sodium levels in the plasma (hypernatraemia); permanent neurological damage is common under such conditions.

Fluoride toxicity due to dissolution of fluoride containing rocks was a major concern in the area and few samples were

reported for nitrate toxicity. One of the essential elements for maintaining normal development of healthy teeth and bones is fluoride. Lower concentrations of fluoride usually below 0.6 mg/l may contribute to dental caries. However, continuing consumption of higher concentrations above 1.5 ppm may cause dental fluorosis and in extreme cases even skeletal fluorosis. Concentrations of fluoride in samples

Table 3 Analytical results (mean values) of groundwater samples in Gang Canal catchment area (site 3)

Sample ID	No. of samples	Turbidity (NTU)	pH	EC ($\mu\text{S}/\text{cm}$)	TDS (mg/l)	TH (mg/l)	Ca (mg/l)	Mg (mg/l)
GC1	5	2.94	7.57 (0.6)	2980 (654)	1297.39 (321)	815 (32.7)	186.4 (34.6)	141.12 (26.6)
GC2	6	3.27	7.40 (1.2)	2480 (324)	1092.11 (276)	748 (22.0)	138 (67.0)	96.84 (8.9)
GC3	8	2.29	7.20 (0.5)	5450 (482)	2120.09 (437)	1451 (410)	283 (34.3)	178.56 (23.7)
GC4	6	13.72	7.46 (0.4)	2880 (536)	1193.71 (127)	743 (45.0)	127 (20.2)	102.24 (12.6)
GC5	6	1.50	7.27 (0.8)	5680 (348)	2281.56 (427)	1656.67 (321)	276.6 (12.8)	231.6 (23.5)
GC6	3	1.93	7.32 (0.8)	9270 (265)	3365.22 (437)	2123 (128)	317.4 (67.7)	319.2 (16.8)
GC7	3	2.13	7.46 (0.9)	7270 (276)	2885.36 (387)	1867 (328)	316.6 (33.9)	258 (18.8)
GC8	1	3.0	7.78	4800	1937.19	1660	336	196.8
GC9	3	5.57	7.33 (0.6)	3720 (328)	1589.46 (606)	1180 (456)	220 (45.5)	151.2 (23.1)
GC10	2	11.95	7.63 (0.5)	2080 (623)	971.48 (57.9)	685 (43.3)	109 (10.9)	99 (7.8)
GC11	2	14.05	7.53 (0.8)	5050 (432)	2326.85 (307)	1625 (421)	292 (56.9)	214.8 (34.4)
GC12	2	3.2	7.48 (0.6)	4650 (610)	2063.44 (653)	1460 (180)	277 (32.9)	184.2 (22.1)
GC13	2	2.05	7.67 (0.8)	11,750 (724)	4305.96 (287)	2915 (203)	529 (27.8)	382.2 (17.8)
GC14	4	15.78	7.28 (0.7)	2000 (109)	934.98 (453)	740 (58.9)	141.6 (67.7)	92.76 (8.7)
GC15	4	1.40	7.38 (0.4)	4160 (287)	1694.54 (287)	1097.5 (74.8)	202.6 (56.6)	141.96 (6.7)
GC16	11	15.24	7.53 (0.6)	2260 (876)	992.13 (87.5)	663 (43.8)	119.4 (20.5)	87.36 (8.9)
GC17	3	11.13	7.75 (0.4)	1590 (328)	749.49 (50.6)	530 (45.9)	88.6 (10.9)	74.04 (5.6)
GC18	4	4.18	7.67 (0.7)	5150 (554)	2199.48 (586)	1504 (254)	294.2 (43.3)	199.8 (23.4)
GC19	12	3.48	7.44 (0.8)	5770 (336)	2297.18 (387)	1688.33 (834)	322.6 (17.7)	211.56 (10.9)
GC20	2	0.35	7.58 (0.9)	2120 (374)	1003.06 (178)	670 (49.9)	124 (39.9)	86.4 (10.2)
GC21	1	14.20	7.36	4500	1873.64	1440	290	171.6
GC22	4	6.04	7.60 (0.5)	2760 (331)	1220.05 (265)	757.50 (37.7)	133.6 (34.4)	101.76 (33.2)
GC23	2	0.45	7.61 (0.7)	9700 (213)	3827.51 (523)	2295 (278)	336 (56.6)	349.2 (23.2)
GC24	4	1.85	7.74 (0.6)	8300 (276)	3375.76 (543)	2150 (478)	356 (17.9)	302.4 (21.9)
Sample ID	No. of samples	Na (mg/l)	K (mg/l)	F (mg/l)	Cl (mg/l)	HCO ₃ (mg/l)	NO ₃ (mg/l)	SO ₄ (mg/l)
GC1	5	123.74 (34.4)	15.21 (7.8)	3.50 (0.7)	540.31 (23.7)	464.82 (28.8)	7.38 (0.6)	49.44 (1.6)
GC2	6	193.89 (12.6)	13.65 (8.0)	2.58 (0.5)	436.65 (55.0)	306.83 (56.6)	11.57 (0.5)	47.04 (2.3)
GC3	8	401.81 (23.2)	19.89 (8.8)	2.88 (0.5)	965.245 (28.8)	416.63 (12.8)	8.32 (0.7)	55.68 (2.4)
GC4	6	227.01 (11.5)	11.7 (6.9)	1.50 (0.6)	530.015 (15.5)	331.23 (28.8)	6.62 (0.8)	25.92 (2.5)
GC5	6	272.78 (21.6)	27.69 (6.0)	2.83 (0.4)	1204.16 (87.9)	341.6 (54.9)	5.92 (0.5)	90.24 (6.5)
GC6	3	529 (23.3)	21.45 (7.9)	2.83 (0.4)	1863.75 (123)	370.27 (39.5)	11.38 (0.6)	97.44 (7.8)
GC7	3	463.45 (45.5)	21.84 (9.8)	2.33 (0.7)	1477.865 (109)	480.07 (81.0)	9.55 (0.5)	95.52 (8.0)
GC8	1	252.77	15.21	2.5	759.7	524.6	21.85	90.24
GC9	3	237.13 (22.8)	8.58 (0.9)	2.5 (0.3)	656.75 (28.8)	434.93 (20.8)	13.58 (0.7)	83.04 (6.9)
GC10	2	130.87 (23.3)	8.97 (0.8)	2.0 (0.7)	392.275 (78.9)	347.7 (12.9)	10.15 (0.8)	46.56 (6.0)
GC11	2	332.58 (13.5)	11.7 (1.2)	2.0 (0.4)	1098.725 (56.9)	536.8 (28.8)	11.82 (0.7)	95.04 (5.7)
GC12	2	340.17 (12.8)	9.75 (0.6)	2.25 (0.4)	898.15 (39.9)	463.6 (43.3)	29.52 (0.4)	91.2 (7.9)
GC13	2	579.14 (22.0)	25.35 (2.1)	2.50 (0.6)	2488.55 (287)	359.9 (28.9)	7.97 (0.6)	110.88 (8.9)
GC14	4	91.08 (45.9)	17.16 (3.8)	2.63 (0.4)	356.065 (45.5)	332.45 (45.9)	25.74 (0.4)	43.68 (5.9)
GC15	4	339.71 (23.5)	14.82 (3.6)	1.63 (0.2)	739.465 (49.9)	414.8 (29.3)	5.59 (0.8)	41.76 (6.8)
GC16	11	161.92 (48.8)	8.97 (0.8)	1.77 (0.5)	436.65 (12.6)	278.16 (10.7)	3.93 (0.9)	34.56 (5.9)
GC17	3	95.22 (10.1)	5.46 (0.5)	1.0 (0.6)	294.65 (17.7)	325.13 (43.9)	6.58 (0.7)	21.12 (5.5)
GC18	4	338.33 (23.8)	10.92 (1.9)	2.38 (0.4)	857.325 (23.7)	390.4 (28.8)	4.32 (0.5)	97.44 (6.0)
GC19	12	338.33 (22.4)	13.26 (1.7)	2.58 (0.6)	1103.695 (12.8)	410.53 (33.2)	5.10 (0.8)	95.52 (9.2)
GC20	2	133.17 (11.5)	4.29 (0.6)	1.50 (0.7)	422.45 (17.5)	329.4 (43.2)	9.03 (0.6)	58.08 (4.8)
GC21	1	252.77 (11.8)	11.31	3.0	766.8 (23.2)	536.8	20.65	90.24
GC22	4	207.92 (10.6)	5.07 (0.5)	3.13 (0.4)	507.65 (12.8)	359.9 (21.2)	5.19 (0.5)	78.24 (4.0)

Table 3 (continued)

Sample ID	No. of samples	Na (mg/l)	K (mg/l)	F (mg/l)	Cl (mg/l)	HCO ₃ (mg/l)	NO ₃ (mg/l)	SO ₄ (mg/l)
GC23	2	591.79 (23.8)	21.45 (4.5)	3.25 (0.5)	2232.95 (432)	353.8 (34.8)	6.96 (0.8)	109.92 (8.9)
GC24	4	427.8 (12.8)	30.81 (5.8)	1.88 (0.4)	1532.18 (189)	334.28 (23.3)	65.14 (245.9)	68.16 (6.8)

Table 4 Groundwater samples of the study area exceeding the recommended permissible limits for drinking purposes

Parameter	BIS (2003)	WHO (2004)		Range and percent samples exceeding the permissible limit as per BIS					
		Most desirable	Maximum allowable	Site 1		Site 2		Site 3	
				Range	Percent samples	Range	Percent samples	Range	Percent samples
pH	6.5–8.5	6.5	8.5	7.20–9.62	14	7.13–8.74	19	7.0–8.01	Nil
EC (μS/cm)	3000	1400	–	310–9100	41	460–13,900	70	460–17,900	69
TDS (mg/l)	2000	500	1500	219.88–2586.97	14	307.99–4700.20	39	224.2–6897.29	44
TH (mg/l)	600	100	500	35–1965	57	135–2840	69	133–4210	73
Ca ⁺² (mg/l)	200	75	200	2.0–332	20	4.0–420	19	22–530	58
Mg ⁺² (mg/l)	100	50	150	6.0–366.0	49	13.2–546	56	20.4–692.4	72
Na ⁺ (mg/l)	200	–	200	13.11–804.08	23	24.38–1009.7	80	11.5–852.38	58
K ⁺ (mg/l)	10	–	12	1.56–26.91	59	5.07–31.59	59	1.56–95.94	62
F ⁻ (mg/l)	1.5	–	1.5	0.5–8.0	42	0.5–8.5	78	0.5–5.0	82
Cl ⁻ (mg/l)	1000	200	600	24.85–1533.6	7	24.85–2403.35	23	56.8–4487.2	33
NO ₃ ⁻ (mg/l)	45	45	–	3.70–82.11	5	0.34–50.76	1	0.50–278.68	2
SO ₄ ⁻² (mg/l)	200	200	400	0.48–188.64	Nil	5.76–190.08	Nil	2.88–116.64	Nil
Turbidity (NTU)	10	–	–	0.3–8.0	Nil	0.1–25.0	6	0.7–60.0	23

Table 5 Classification of groundwater samples based on TDS (Davis and De Wiest 1966)

TDS (mg/l)	Water type	Percent samples		
		Site 1	Site 2	Site 3
< 500	Desirable for drinking	21	08	14
500–1000	Permissible for drinking	27	12	13
< 3000	Useful for irrigation	50	67	62
> 3000	Unfit for drinking and irrigation	02	13	11

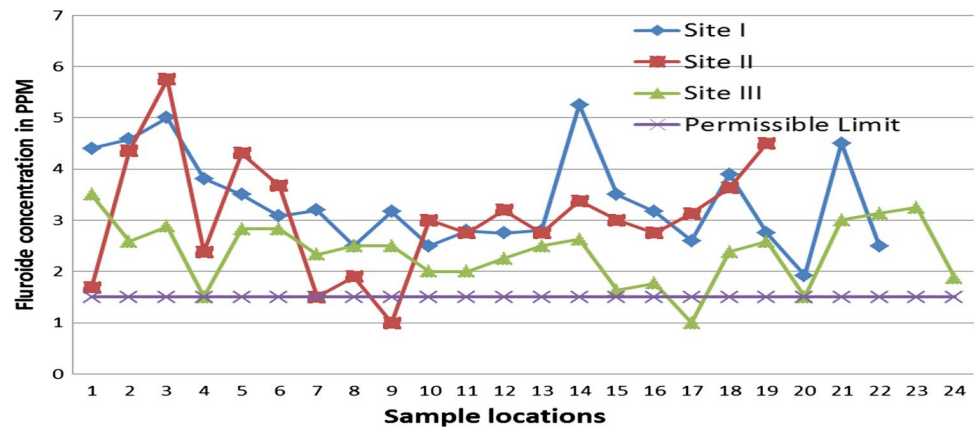
Table 6 Sawyer and McCarthy's (Sawyer and McMcarty 1967) classification of groundwater based on hardness

TH as CaCO ₃ (mg/l)	Water class	Percent samples		
		Site 1	Site 2	Site 3
< 75	Soft	03	00	00
75–150	Moderately hard	10	03	02
150–300	Hard	13	08	10
> 300	Very hard	74	89	88

taken from the study area varied from 0.5 to 8.0 ppm (site 1), 0.5 to 8.5 ppm (site 2) and 0.5 to 5.0 ppm (Site 3) with different mean values as shown in Fig. 2 (Chaudhary et al. 2008, 2009). There may therefore be the likelihood of the risk of dental caries, suffered by people who depend on this water source for drinking. A high rate of evapotranspiration, longer residence time of waters in the aquifer zone, intensive and long-term irrigation and heavy use of fertilizers are the supplementary factors to further increase the F⁻ content in the groundwaters (Subba Rao 2003). Very high levels of F⁻ and other physicochemical parameters were observed and discussed in the study conducted in different villages of Haryana (Meenakshi et al. 2004).

The Cl⁻ content was observed in the range of 24.85–4487.2 mg/l, and maximum was reported in 56 LNP village in Gang catchment. Thirty-three percent of groundwater samples in Gang catchment and 23% in Bhakra catchment were found with exceeding level of Cl⁻ prescribed by BIS 1000 mg/l. Only 8% of groundwater samples were having higher concentration of NO₃⁻ in all the samples, and maximum 278.68 mg/l was observed only in one water sample from Bhagwansar-chunavad 31GG (Gang catchment). NO₃⁻ is considered relatively non-toxic, but at the higher concentration in drinking water may cause

Fig. 2 Fluoride concentration (mean values) in three different sites



methaemoglobinemia (in infants). Farmers have been using N-fertilizers in their fields, and leaching of NO_3^- through soil profile is the main reason of nitrate enrichment in the local aquifer as water infiltration rate is comparatively higher in this region (Chaudhary et al. 2010). The SO_4^{2-} content varied from 0.48 to 190.08 mg/l, and all were within the permissible range as decided by WHO (400 mg/l) and BIS (200 mg/l). SO_4^{2-} in groundwater mainly occurs due to sulfate mineral dissolution and sulfide mineral oxidation (Krouse and Mayer 1999).

The abundance of major ions was found in the following order:

$\text{Na}^+ > \text{Ca}^{+2} > \text{Mg}^{+2} > \text{K}^+ = \text{Cl}^- > \text{HCO}_3^- > \text{SO}_4^{2-} > \text{NO}_3^- > \text{F}^-$
Thus, sodium and chloride ions were found to be comparatively higher in concentration and major cause of elevated levels of EC in the study area.

Hydrogeochemical facies

The piper diagram carried out by Rockworks16 software was used to identify the hydrogeochemical facies of groundwater in the three canal catchment areas of northwest Rajasthan. As shown in Fig. 3, about 91% (site 1), 36.9 (site 2), 100 (site 3) of water samples fall in zone of no dominant cation type and 9% (site 1), 73.7% (site 2) of water samples fall in zone of Na^+ sodium type. For the predominate anion, it is clearly indicated that the chloride-type sample fallen in 68% (site 1), 84.2% (site 2), 84.2% (site 3) shows that the prominent hydrogeological facies followed by site 1 fall in mixed CaNaHCO_3 , CaHCO_3 , NaCl , CaMgClSO_4 ; site 2 water samples fall in CaCl , NaCl , NaKClSO_4 ; site-3 water samples fall in CaCl , CaMgClSO_4 (Table 7). The diagram also shows that there are different water types present in the groundwater systems. These trilinear diagrams are beneficial in bringing out chemical relationships among groundwater samples rather than plotting methods (Piper 1944; Back and Hanshaw 1965).

Irrigation suitability

Irrigated agriculture is dependent on an adequate water supply of usable quality. Conceptually, water quality refers to the characteristics of a water supply that will influence its suitability for a specific use (Kumar et al. 2007).

The northern part of the study area is characterized by arid soils which are light yellowish brown to pale in color with calcareous concretions in the depth range of 75–100 cm. Soils are deep and moderately drained. Permeability is moderate to moderately low, and water holding capacity and natural fertility are generally poor. Loamy sand and sandy loam are the predominant types of soil met within this soil group. At places, patches of sand also occur. The southern portion of the region is characterized by desert soils, which are very pale brown to yellowish brown in color and are generally devoid of lime concretions. Soils are generally well drained to excessively drained and have low moisture holding capacity and high permeability. So, in the poor soil conditions, irrigation water quality matters for good agriculture practices.

This section reveals the variation in the levels of the parameters and its suitability for agriculture practice (Tables 8, 9, 10).

Salinity index

Electrical conductivity is a useful and reliable index for the measurement of water salinity or total dissolved solids in water. Electrical conductivity in water is due to ionization of dissolved inorganic solids—minerals, salts, metals, cations or anions that dissolved in water. It is evident from the data in Table 11 that majority of the groundwater samples in the study were under high salinity class and suitable only for irrigating medium and high salt-tolerant crops. Salinity occurs due to weathering of rocks and release of soluble salts in the groundwater, mainly chlorides of sodium, calcium and magnesium and to a lesser extent, sulfates and carbonates.

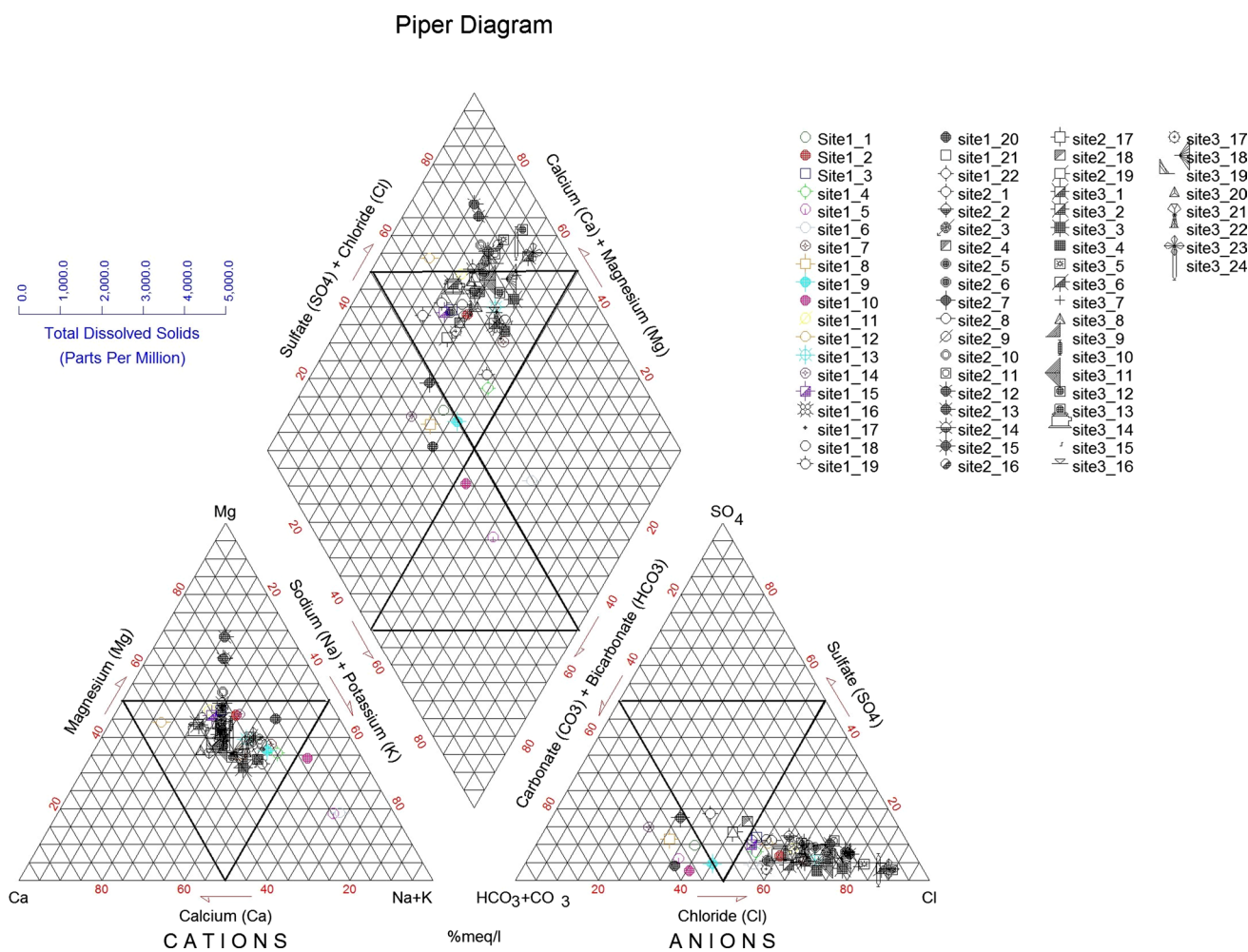


Fig. 3 Piper trilinear diagram for sites 1, 2 and 3

Table 7 Variation in hydrochemical facies for sites 1, 2 and 3

Subdivision of diamond	Diamond-shaped fields	Site 1		Site 2		Site 3	
		No. of samples	%	No. of samples	%	No. of samples	%
Cations	A Calcium type	–	–	–	–	–	–
	B No dominant	20	91	5	26.3	24	100
	C Magnesium type	–	–	–	–	–	–
	D Sodium type	2	9	14	73.7	–	–
Anions	E Bicarbonate type	7	31.8	1	5.2	–	–
	B No dominant	–	–	2	10.6	–	–
	F Sulfate type	–	–	–	–	–	–
	G Chloride type	15	68.2	16	84.2	24	100

Typically, irrigation water salinity in arid and semiarid areas is greater than that of humid and sub-humid areas (Bauder et al. 2007). High salinity of irrigation water is responsible for salt accumulation in the root zone and leads to damage in plant cells (Greenway and Munns 1980). Plants absorb

water through a process of ‘osmo-regulation,’ and when the soil solution salinity is greater than the internal salinity of the plant, water uptake is restricted. High salinity can also lead to physiological drought conditions and ion toxicity (Zhu 2002).

Table 8 Irrigation water quality parameters (mean values in meq/l) of groundwater samples in Indira Gandhi Canal catchment area (site 1)

Sample ID	No. of sam- ples	PS	%Na	SAR	KI	RSC	RSBC	MH	Mg/Ca	PI
IGC1	5	3.995	35.41315	2.20	0.548303	2.80	3.42	63.70757	1.88	55.19785
IGC2	6	13.6	28.17077	2.56	0.392191	–	–0.09	65.63991	2.23	36.35815
IGC3	4	8.695	23.44454	1.82	0.306243	–	0.57	63.60424	2.23	34.52004
IGC4	11	9.22	43.38776	3.87	0.766402	3.17	2.07	64.45566	1.80	53.25211
IGC5	7	5.765	66.10268	14.59	1.950086	9.63	7.46	56.28227	1.56	83.722
IGC6	6	9.57	67.631	6.48	2.089376	5.33	4.93	59.52782	1.45	81.65169
IGC7	5	17.475	40.69249	4.37	0.686127	–	1.68	65.78035	2.24	49.31494
IGC8	2	3.14	34.3696	1.99	0.523684	–	3.6	55.26316	1.40	56.15043
IGC9	3	8.25	40.32342	3.52	0.675699	3.90	5.4	62.67483	3.57	55.33263
IGC10	3	4.61	50.28902	3.10	1.011628	4.17	5.24	72.28682	4.7	71.98002
IGC11	7	12.8	21.10429	1.81	0.267496	–	–3.62	61.46967	1.67	28.43122
IGC12	4	7.785	10.99531	0.69	0.123536	–	–3.18	50.64403	1.15	22.6171
IGC13	5	16.59	34.19355	3.48	0.519608	–	–1.72	61.17647	1.74	41.70111
IGC14	2	1.71	28.50838	1.60	0.398765	–	3.3	66.66667	2.05	49.13053
IGC15	3	7.835	22.45455	2.46	0.289566	5.2	–0.4	60.551	6.63	33.46476
IGC16	6	14.425	37.56801	3.76	0.601743	0.30	–1.67	62.22222	1.67	44.24779
IGC17	5	14.19	39.93447	3.54	0.664848	–	0.54	62.06061	1.68	48.92858
IGC18	5	20.94	38.44394	4.37	0.624535	–	–1.4	63.56877	1.84	44.60666
IGC19	2	10.685	41.39584	3.16	0.706364	3.3	2.25	56.81818	1.80	54.61852
IGC20	6	1.915	36.60714	1.49	0.577465	1.53	2.43	74.64789	4.67	66.34981
IGC21	2	18.22	25.0673	2.38	0.334531	–	–3.1	55.68862	1.25	33.21015
IGC22	2	9.59	20.61069	1.88	0.259615	–	–2.9	58.07692	1.40	28.95534

Table 9 Irrigation water quality parameters (mean values in meq/l) of groundwater samples in Bhakra Canal catchment area (site 2)

Sample ID	No. of sam- ples	PS	%Na	SAR	KI	RSC	RSBC	MH	Mg/Ca	PI
BC1	8	7.03	38.09074	2.87	0.615267	2.10	3.69	76.64122	24.89	49.59552
BC2	7	18.955	57.36531	6.61	1.345508	1.43	2.51	58.87509	1.34	65.65762
BC3	2	30.865	53.80887	9.16	1.164918	1.90	–3.4	60.98361	1.65	57.77799
BC4	8	26.395	53.61871	7.40	1.156042	1.0	–0.51	59.51475	1.43	59.46608
BC5	8	23.98	57.0229	7.59	1.326821	2.0	0.65	58.67377	1.36	63.56628
BC6	3	15.295	69.24129	9.57	2.251111	5.17	5.5	64.77778	1.87	78.68595
BC7	3	5.905	68.55346	6.45	2.18	–	6.3	56.90909	1.57	84.18538
BC8	5	18.035	38.72201	4.0	0.631907	–	0.82	60.87344	1.48	46.57247
BC9	6	17.575	41.27132	4.22	0.702746	–	1.41	55.54382	1.30	50.60087
BC10	6	30.425	57.80622	9.31	1.370017	–	0.55	68.45754	2.23	62.37444
BC11	2	23.82	51.6129	7.35	1.066667	–	–3.6	58.73016	1.65	56.26541
BC12	5	36.93	41.07066	6.32	0.696948	–	–2.26	76.11434	69.24	44.61131
BC13	2	36.25	53.50691	8.31	1.150857	–	2	80.95238	28.75	57.73283
BC14	4	20.91	54.53883	7.41	1.19968	1.30	1.07	65.67005	29.28	60.64136
BC15	7	27.705	46.94486	6.69	0.884831	–	–2.21	63.04173	1.51	52.05681
BC16	2	33.695	58.02446	9.30	1.38234	–	–2.6	59.8234	1.60	62.25319
BC17	15	20.29	54.66329	6.74	1.205718	1.67	1.02	57.05407	1.31	62.09062
BC18	4	9.185	54.9325	4.52	1.218894	2.25	2.55	57.37327	1.78	67.07692
BC19	3	12.25	57.37822	6.63	1.346218	6.0	4.7	58.23529	1.43	68.02867

Table 10 Irrigation water quality parameters (mean values in meq/l) of groundwater samples in Gang Canal catchment area (site 3)

Sample ID	No. of samples	PS	%Na	SAR	KI	RSC	RSBC	MH	Mg/Ca	PI
GC1	5	15.735	20.33258	1.65	0.255218	–	–1.7	55.78748	1.26	30.31819
GC2	6	12.79	36.02564	2.62	0.563126	–	–1.87	53.90782	1.28	44.93796
GC3	8	27.77	37.56989	4.48	0.601791	–	–7.32	51.25732	1.06	42.72161
GC4	6	15.2	39.89491	2.97	0.663753	0.40	–0.92	57.29657	1.42	48.72299
GC5	6	34.86	26.36141	2.79	0.357984	1.40	–8.23	58.25536	1.48	31.13005
GC6	3	53.515	35.13059	4.98	0.541559	–	–9.8	62.63245	1.67	38.56973
GC7	3	42.625	35.05567	4.66	0.53978	–	–7.96	57.59443	1.37	39.55092
GC8	1	22.34	24.86988	2.70	0.331024	–	–8.2	49.39759	1.0	31.23054
GC9	3	19.365	30.40401	2.83	0.436864	–	–3.87	53.38983	1.13	38.03166
GC10	2	11.535	29.34502	1.82	0.415328	–	0.25	60.21898	1.65	41.16956
GC11	2	31.94	30.79216	3.56	0.444923	–	–5.8	55.07692	1.20	36.87363
GC12	2	26.25	33.62128	3.84	0.506507	–	–6.25	52.56849	1.20	39.66277
GC13	2	71.255	30.16291	4.68	0.431904	–	–20.55	54.63122	1.20	32.81706
GC14	4	10.485	21.0975	1.49	0.267387	–	–1.63	52.19446	1.13	32.76691
GC15	4	21.265	40.21236	4.18	0.672587	–	–3.33	53.87067	1.28	46.82749
GC16	11	12.66	34.6969	2.41	0.531321	–	–1.41	54.9434	1.28	44.7145
GC17	3	8.52	28.08684	1.38	0.390566	–	0.9	58.20755	1.33	43.3379
GC18	4	25.165	31.92967	3.79	0.469069	–	–8.31	53.09311	1.23	37.19487
GC19	12	32.085	30.34867	3.56	0.435723	–	–9.4	52.22156	1.11	35.45221
GC20	2	12.505	30.17196	2.04	0.43209	–	–0.8	53.73134	1.35	42.04036
GC21	1	22.54	27.62001	2.90	0.381597	–	–5.7	49.65278	1.0	34.82156
GC22	4	15.115	37.35537	3.15	0.596306	–	–0.78	55.93668	1.33	47.1393
GC23	2	64.045	35.9207	5.38	0.560566	–	–11	63.39869	1.70	38.98354
GC24	4	43.87	30.19481	3.81	0.432558	–	–12.32	58.60465	1.43	33.56458

Doneen (1964b) described potential salinity of irrigation water by pointing out that the suitability of water for irrigation is not only dependent on the concentration of soluble salts. It has been reported that the low-solubility salts precipitate and accumulate in the soil for successive irrigation, whereas the concentration of highly soluble salts increases the salinity of the soil (Siamak and Srikantaswamy 2009). The average potential salinity of the study area varied from 1.71 to 17.48, 5.91 to 33.70 and 8.52 to 71.26 for sites 1, 2 and 3, respectively. It has been reported that chloride is not adsorbed by soils, but it moves readily with the soil–water

into the crop. It travels in the transpiration stream and accumulates in the leaves. Thus, excessive chloride could cause necrosis (dead tissue) in plants which is often accompanied by early leaf drop or defoliation (Ayers and Westcot 1994).

Sodium percentage (%Na)

Sodium is one of the important metals that serve as essential nutrients necessary for some biochemical functions. It is often found in natural waters due to its high solubility and frequently associated with salinity problems when linked to chloride and sulfate ions. Percent sodium is widely utilized to assessing the suitability of water for irrigation purposes (Wilcox 1948). The % Na is computed with respect to relative proportions of cations present in water and calculated using the following formula:

$$\text{Na}\% = \text{Na}^+ \times 100 / [\text{Ca}^{+2} + \text{Mg}^{+2} + \text{Na}^+ + \text{K}^+] \text{ (meq/l)}$$

In this regard, the %Na values and the corresponding EC of the waters were plotted within the Wilcox (1955) diagram (Fig. 4) to confirm the irrigation classes of the waters. Indeed, the waters were plotted within the excellent to good

Table 11 Classification of water based on EC (Handa 1969)

EC ($\mu\text{S}/\text{cm}$)	Water salinity	Percent samples		
		Site 1	Site 2	Site 3
0–250	Low	00	00	00
251–750	Medium	13	07	07
751–2250	High	28	16	20
2251–6000	Very high	57	54	48
6001–10,000	Extensively high	02	21	19
10,001–20,000	Extensively high	00	02	06

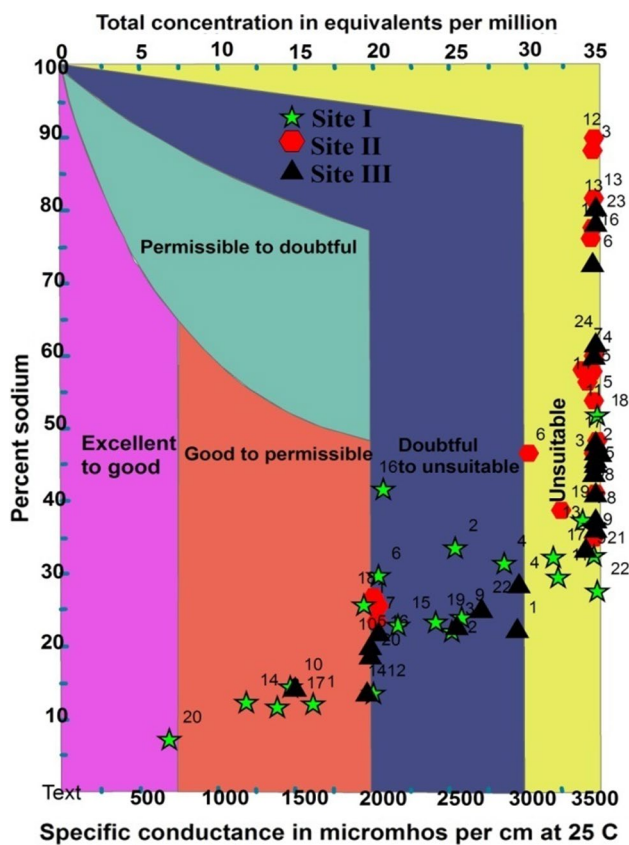


Fig. 4 Wilcox (1955) diagram in the study area

class, but most of the samples belong to doubtful to unsuitable class on account of the high %Na. Considering the irrigation water quality ratings on the basis of %Na (Table 12) reveals that majority of samples fall in good to permissible class but in combination with high electrical conductance making water unsuitable for irrigation use. Dissolution of minerals from lithological compositions and addition of chemical fertilizers are major causes of high Na%. Excess sodium concentration in irrigation water produces the undesirable effects. Soil dispersion is the primary physical process associated with high sodium concentration which is further assigned to reduced infiltration, reduced hydraulic

Table 12 Irrigation water quality of groundwater based on sodium percentage in study area

Sodium (%)	Water class	Percent samples		
		Site 1	Site 2	Site 3
<20	Excellent	17	–	14
20–40	Good	46	21	73
40–60	Permissible	22	51	13
60–80	Doubtful	13	28	–
> 80	Unsuitable	02	–	–

condition and surface crusting (Shainberg and Letey 1984; Hanson et al. 1999; Bardhan et al. 2007). Increasing sodium concentration disperses soil and increasing salinity flocculates soil (Hanson et al., 1999). High Na⁺ interferes with K⁺ and Ca⁺² nutrition in plants and disturbs efficient stomatal opening and results in depression of photosynthesis and growth (Tayakkoli et al. 2010).

Sodium adsorption ratio (SAR)

SAR is an important parameter for the determination of suitability of water for irrigation purpose because it is responsible for the sodium hazard in irrigation water. The proportion of sodium (Na⁺) to calcium (Ca⁺²) and magnesium (Mg⁺²) ions in a water sample is expressed as SAR:

$$SAR = Na^+ / [(Ca^{+2} + Mg^{+2}) / 2]^{0.5} \text{ (meq/l)}$$

The degree to which irrigation water tends to enter into cation exchange reaction in soil can be indicated by the SAR. Excess sodium or high SAR values in waters produce undesirable effects of changing soil properties and reducing soil. Irrigation waters with high SAR tend to cause soils to disperse, form crusts, become compacted and have very low infiltration rate and poor air movement properties. Irrigation waters with high SAR replace adsorbed calcium and magnesium ions with sodium ions on soil particles, and soils tend to become deflocculated and relatively impermeable. Salts present in soil solution move downward while sodium adsorbed on the soil exchange complex does not and may have a different effect on soil physical and chemical properties. A severe reduction in infiltration is likely to occur with the condition of relatively low EC and high SAR. The classification of groundwater samples based on SAR values is shown in Table 13. Majority of samples were found within the range of excellent to good category and for suitable irrigation use (except 2% samples in site 1).

SAR and salinity combination could be used to assess irrigation water quality in relation to infiltration or permeability problem. The US salinity diagram (Fig. 5) illustrates that most of the groundwater samples fall in the field of C₄S₁, indicating very high salinity and low alkalinity hazard and suitable only for crops having good salt-tolerance

Table 13 Classification of irrigation water on SAR values

SAR values	Water quality	Percent samples		
		Site 1	Site 2	Site 3
< 10	Excellent	96	84	100
10–18	Good	02	16	–
19–26	Doubtful	–	–	–
> 26	Unsuitable	02	–	–

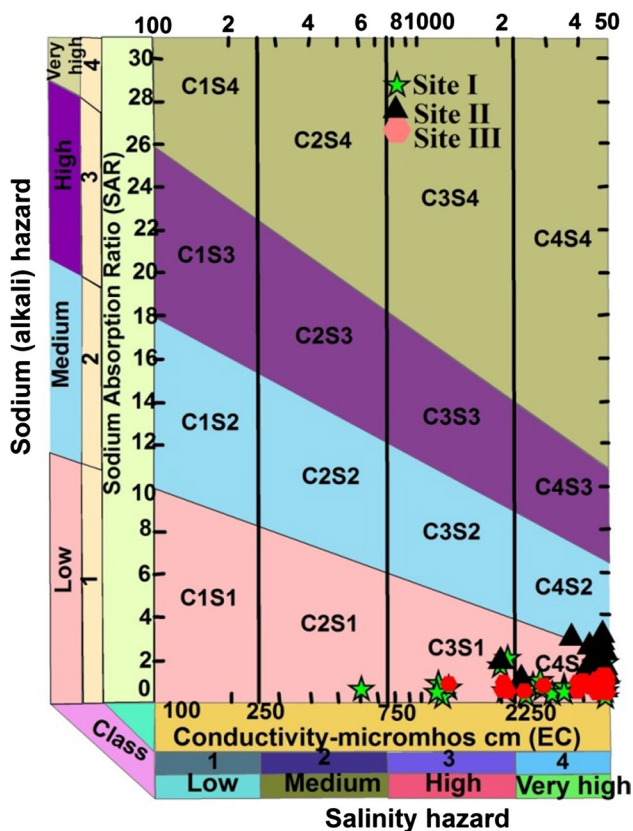


Fig. 5 USSL classification in the study area

capacity. Few samples fall in the field of C₃S₁, indicating high salinity with low sodium content and suitability for irrigation.

Kelly’s index (KI)

Sodium measured against calcium and magnesium is used to calculate KI value (Kelly 1940). However, nowadays, SAR is a more popular parameter to highlight sodium hazard and this parameter is not in common use. KI more than 1 indicates high sodium content and unsuitability for irrigation use, while the samples having KI less than 1 are suitable for irrigation. In the present study, KI values were observed in the ranges 0.12–2.09, 0.62–2.25 and 0.26–0.67 meq/l for sites 1, 2 and 3, respectively.

Residual sodium carbonate (RSC)

The excess sum of carbonate and bicarbonate in groundwater over the sum of calcium and magnesium also influences the quality of water. High carbonate and bicarbonate in water essentially increase the sodium hazard of the water to a level greater than that indicated by the SAR. High carbonate and bicarbonate tend to precipitate calcium carbonate and

Table 14 Groundwater quality based on RSC (Richards 1954)

RSC (meq/l)	Water quality	Percent samples		
		Site 1	Site 2	Site 3
< 1.25	Good	81	84	99
1.25–2.50	Doubtful	03	08	01
> 2.50	Unsuitable	16	08	–

magnesium carbonate when the soil solution is concentrated during soil drying.

RSC is an important parameter to evaluate the suitability of irrigation water and calculated by the following formula:

$$RSC = (HCO_3^- + CO_3^{2-}) - (Ca^{+2} + Mg^{+2}) \text{ (meq/l)}$$

The classification of irrigation water based on RSC values (Table 14) represents that most of the samples belong to good category.

Gupta and Gupta (1987) postulated residual sodium bicarbonate (RSBC) parameter for groundwater suitability and suggested the value <5 mg/L to be most appropriate. It is calculated by the following formula:

$$RSBC = HCO_3^- - Ca^{+2} \text{ (meq/l)}$$

In the study area, RSBC varied between – 3.62 and 7.46, – 3.6 and 6.3 and – 20.55 and 0.9 meq/l for the sites 1, 2 and 3, respectively. Calcium is one of the most abundant natural elements in the environment and generally found in all natural waters. It has higher concentration in water from limestone area when compared to that from non-calcareous area.

Magnesium hazard (MH)

Magnesium content of water is considered as one of the most important qualitative criteria in determining the quality of water for irrigation. A high level of magnesium is usually due to the presence of exchangeable sodium in irrigated soils. MH was introduced by Paliwal (1972) and calculated as

$$MH = Mg^{+2} \times 100 / (Ca^{+2} + Mg^{+2}) \text{ (meq/l)}$$

MH value more than 50% has an adverse affects on the crop yield and soil structure. In the present study area, all the water samples had values more than 50%, which were unsuitable for irrigation purpose. Generally, calcium and magnesium maintain a state of equilibrium in most waters. More magnesium in water will adversely affect crop yields as the soils become more alkaline. Considering the irrigation water quality ratings based on Mg/Ca ratio shows that

Table 15 Classification of irrigation water based on Mg/Ca ratio

Mg/Ca ratio	Water quality	Percent samples		
		Site 1	Site 2	Site 3
< 1.5	Safe	43	57	78
1.5–3.0	Moderate	45	35	22
> 3.0	Unsafe	12	08	–

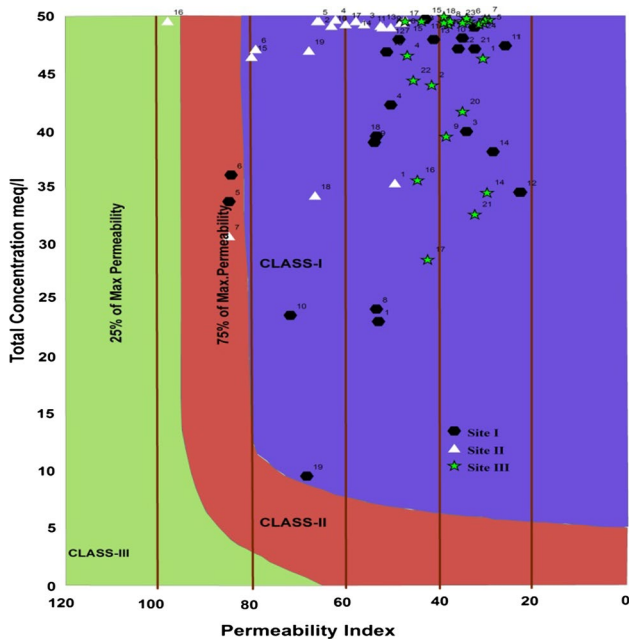


Fig. 6 Doneen classification of irrigation water based on permeability index (PI)

majority of the samples belong to safe and moderate category (Table 15).

Permeability index (PI)

As an extension, Doneen’s (1964a) model for assessing the suitability of water for irrigation based on the PI was also used to classify the waters. PI is calculated by the following equation:

$$PI = \left[Na^+ + (HCO_3^-)^{0.5} \right] \times 100 / [Na^+ + Ca^{+2} + Mg^{+2}]$$

Accordingly, waters can be classified as Class I, Class II and Class III orders. Class I and Class II waters are categorized as good for irrigation with 75% PI or more. Class III water is unsuitable with 25% of maximum permeability. The calculated PI value ranges from 22.62 to 83.72, 44.61 to 84.19 and 30.32 to 48.72 in sites 1, 2 and 3, respectively (Fig. 6).

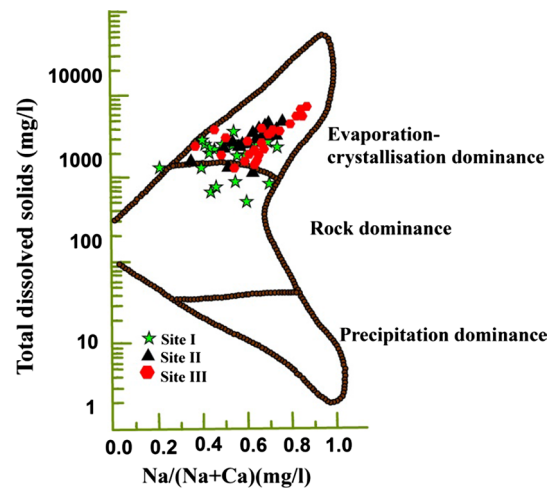


Fig. 7 Gibbs variation diagram (TDS vs. [(Na + K)/(Na + K + Ca)])

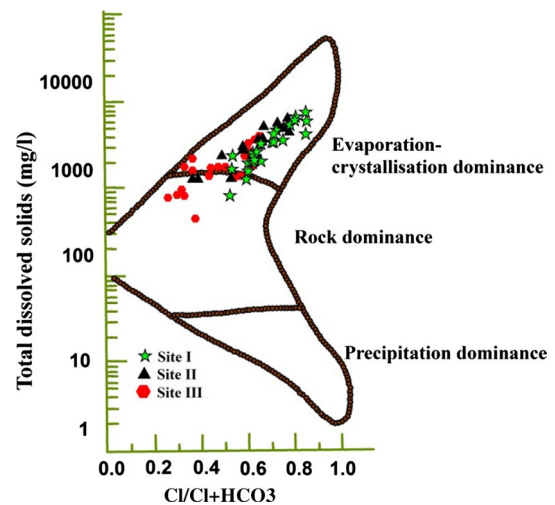


Fig. 8 Gibbs variation diagram (TDS vs. [Cl/(Cl + HCO₃)])

Gibbs groundwater chemistry

Gibbs diagram (Gibbs 1970) represents the ratio 1 for cations [(Na + K)/(Na + K + Ca)] and ratio 2 for anions [Cl/(Cl + HCO₃)] as a function of TDS to assess the groundwater chemistry. Figures 7 and 8 show that majority of the water samples belong to evaporation–crystallization zone which increases salinity by increasing Na⁺ and Cl⁻ with relation to increase of TDS. However, a few samples indicate the dissolution of rock minerals influencing groundwater chemical composition.

Conclusions

The objective of this paper is to help the reader better understanding the geochemistry of groundwater in three different canal catchment areas of northwest Rajasthan. It was found that geology itself is the main cause of deteriorated groundwater quality in this area. High levels of TDS and F^- are major water quality issues in drinking purpose, and community-based quality control equipments should be installed to avoid human health issues. Wise use of nitrogen fertilizers will reduce the risk of nitrate enrichment in groundwater. Mixing of canal water with groundwater could be the safe alternative in both drinking and irrigation. Selection of salt-tolerance species and frequent irrigation might reduce the risk of agricultural damage in the study area.

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References

- APHA (1989) Standard methods for examination of water and wastewater, 17th edn. American Public Health Association, Washington, DC
- APHA (1995) Standard methods for the examination of water and wastewater, 19th edn. American Public Health Association, Washington, DC
- Arumugam K, Elangovan K (2009) Hydrochemical characteristics and groundwater quality assessment in Tirupur Region Coimbatore District, Tamil Nadu, India. *Environ Geol* 58:1509–1520
- Ayers RS, Westcot DW (1994) Water quality for agriculture. *FAO Irrig Drain Pap* 29(1):1–130
- Back W, Hanshaw BB (1965) Chemical geohydrology In: *Advances in hydroscience*, Academic Press, New York, pp 11–49
- Bardhan G, Chaudhari SK, Mohapatra PK (2007) Effect of irrigation water quality on saturated hydraulic conductivity of typical Haplustert, Vertic Haplustept, and Lithic Ustorthent Soils. *J Agric Phys* 7:38–46
- Bauder TA, Cardon GE, Waskam RM, Davis JG (2004) Irrigation water quality-cooperative extension agriculture. Colorado State University, Colorado
- Bauder TA, Waskom RM, Davis JG (2007) Irrigation water quality criteria, US Department of Agriculture, Colorado State University, Colorado
- Bureau of Indian Standards (2003) Drinking water-specification IS: 10500. BIS, New Delhi
- Chaudhary V, Sharma M, Yadav BS (2008) Assessment of water fluoride toxicity levels in northwest Rajasthan, India. *Fluoride* 41(3):212–215
- Chaudhary V, Sharma M, Yadav BS (2009) Elevated fluoride in canal catchment soils of northwest Rajasthan, India. *Fluoride* 42(1):46–49
- Chaudhary V, Kumar M, Sharma M, Yadav BS (2010) Fluoride, boron and nitrate toxicity in groundwater of northwest Rajasthan, India. *Environ Monit Assess* 161:343–348
- Davis SN, DeWiest RJ (1966) *Hydrogeology*. Wiley, New York
- Doneen LD (1964a) Notes on water quality in agriculture. Published as a water science and engineering paper, 4001, Department of Water Science and Engineering, University of California
- Doneen LD (1964b) Notes on water quality in agriculture. *Water Science and Engineering*, University of California, Davis
- Drever JI (1988) *The geochemistry of natural water* Englewood Cliffs, vol 437. Prentice Hall, New Jersey
- Fianko JR, Nartey VK, Donkor A (2010) The hydrochemistry of groundwater in rural communities within the Tema District, Ghana. *Environ Monit Assess* 168:441–449
- Garg VK, Suthar S, Singh S, Sheoran A (2009) Drinking water quality in villages of southwestern Haryana, India: assessing human health risks associated with hydrochemistry. *Environ Geol* 58:1329–1340
- Gibbs RJ (1970) Mechanisms controlling world water chemistry. *Science* 170(3962):1088–1090
- Gleeson T, Yoshihidewada BM, Beek LPH (2012) Water balance of global aquifers revealed by groundwater footprint. *Nature* 488:197–200
- Greenway H, Munns R (1980) Mechanism of salt tolerance in non halophytes. *Ann Rev Plant Physiol* 3(1):149–190
- Gupta AK, Gupta IC (1987) *Management of saline soils and waters*. Oxford and IBH Publishing Company, New Delhi
- Handa BK (1969) Description and classification of media for hydro-geochemical investigations. In: *Symposium on ground water studies in arid and semiarid regions*, Roorkee
- Hanson B, Grattan SR, Fulton A (1999) *Agricultural salinity and drainage*. University of California Irrigation Program. University of California, Davis
- Hem JD (1985) Study and interpretation of the chemical characteristics of natural water. *USGS, Water Supply* 2254 (264):117–120 in India. *Nature* 460:999–1002
- Jain CK, Bandyopadhyay A, Bhadra AA (2010) Assessment of groundwater quality for drinking purpose, District Nainital Uttarakhand, India. *Environ Monit Assess* 166:663–676
- Kelly WP (1940) Permissible composition and concentration of irrigation waters. *Proc ASCE* 66:607
- Krouse HR, Mayer B (1999) Sulfur and oxygen isotopes in sulphate. In: *Herczeg AL, Cook PG (eds) Environmental tracers in subsurface hydrology*. Kluwer, Dordrecht, pp 195–231
- Kumar M, Kumari K, Ramanathan AL, Saxena R (2007) A comparative evaluation of groundwater suitability for irrigation and drinking purposes in two intensively cultivated districts of Punjab, India. *Environ Geol* 53:553–574
- Kumar SK, Rammohan V, Sahayam JD, Jeevananadam M (2009) Assessment of groundwater quality and hydrogeochemistry of Manimuktha river basin, Tamil Nadu, India. *Environ Monit Assess* 159:341–351
- Kurdi M, Tabasi S, Eslamkish T, Hezarkhani A (2013) Hydrogeochemical study to evaluate the suitability of water for irrigation purpose at Qareh sou catchment, North of Iran. *Elixir*
- Little J, Kalischuk A, Gross D, Sheedy C (2010) *Assessment of Water Quality in Alberta's Irrigation Districts*. Alberta Agriculture and Rural Development, Alberta, Canada
- MacDonald AM, Bonsor HC, Ahmed KM et al (2016) Groundwater quality and depletion in the Indo-Gangetic basin mapped from in situ observations. *Nat Geosci*. <https://doi.org/10.1038/ngeo2791>
- Meenakshi GV, Kavita R, Malik A (2004) Groundwater quality in some villages of Haryana, India: focus on fluoride and fluorosis. *J Hazard Mater* 106:85–97

- Paliwal KV (1972) Irrigation with saline water. Monogram no. 2, new series 198, IARI, New Delhi
- Piper AM (1944) A graphical procedure in the geochemical interpretation of water analysis. *Am Geophys Union Trans* 25:914–928
- Rajmohan N, Elango L (2005) Nutrient chemistry of groundwater in an intensively irrigated region of Southern India. *Environ Geol* 47:820–830
- Richards LA (1954) Diagnostics and improvement of saline and alkaline soils. U.S. Dept. of Agriculture hand book no. 60. U.S. Salinity Laboratory, Washington, DC
- Rodell M, Velicogna I, Famiglietti JS (2009) Satellite-based estimates of groundwater depletion in India. *Nature* 460(7258):999–1002
- Salifu M, Yidana SM, Osae S, Armah YS (2013) The influence of the unsaturated zone on the high fluoride contents in groundwater in the Middle Voltaian Aquifers—the Gushegu District, Northern Region of Ghana. *J Hydrogeol Hydrol Eng* 2:2
- Sarkar AA, Hassan AA (2006) Water quality assessment of a groundwater basin in Bangladesh for irrigation use. *Pak J Biol Sci* 9(9):1677–1684
- Sawyer GN, McMcarty DL (1967) Chemistry of sanitary engineers, 2nd edn. McGraw Hill, New York
- Sengupta P (2013) Potential health impacts of hard water. *Int J Prev Med* 4(8):866–875
- Shainberg I, Letey J (1984) Response of soils to sodic and saline conditions. *Hilgardia* 61:21–57
- Siamak G, Srikantaswamy S (2009) Analysis of agricultural impact on the Cauvery river water around KRS dam. *World Appl Sci J* 6(8):1157–1169
- Stallard RF, Edmond JM (1983) Geochemistry of the Amazon 2. The influence of geology and weathering environment on the dissolved load. *J Geophys Res* 88:9671–9688
- Subba Rao N (2003) Groundwater quality: focus on fluoride concentration in rural parts of Guntur district, Andhra Pradesh, India. *Hydrol Sci* 48(5):835–847
- Subba Rao N, Prakasa Rao J, Devadas JD, Srinivasa Rao KV, Krishna C, Nagamalleswara Rao B (2002) Hydrogeochemistry and groundwater quality in a developing urban Environment of a semi-arid region, Guntur, Andhra Pradesh, India. *J Geol Soc India* 59:159–166
- Subramani T, Elango L, Damodarasamy SR (2005) Groundwater quality and its suitability for drinking and agricultural use Chithar River Basin, Tamil Nadu, India. *Environ Geol* 47:1099–1110
- Tayakkoli E, Rengasamy P, McDonald E (2010) High concentrations of Na⁺ and Cl⁻ ions in soil solution have simultaneous detrimental effects on growth of faba bean under salinity stress. *J Exp Bot* 61(15):4449–4459
- Todd DK (1980) Groundwater hydrology, 2nd edn. Wiley, New York
- USSL (1954) Diagnosis and improvement of saline and alkali soil. USDA Hand Book no. 60, Washington
- WHO (2004) Guidelines for drinking water quality: training pack. WHO, Geneva
- Wilcox LV (1948) The quality of water for irrigation uses. US Dept Agri Tech Bull 962. USDA, Washington, DC
- Wilcox LV (1955) Classification and use of irrigation waters. USDA, Circular 969, Washington, DC
- Zhu JK (2002) Salt and drought stress signal transduction in plants. *Annu Rev Plant Biol* 53:247–273

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