

A comparative evaluation of groundwater suitability for irrigation and drinking purposes in two intensively cultivated districts of Punjab, India

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Abstract Punjab is the most cultivated state in India with the highest consumption of fertilizers. Patiala and Muktsar districts are two agricultural dominated districts of Punjab located in extreme south-east and south-west of the state. This paper highlights temporal variations of the groundwater quality and compares its suitability for irrigation and drinking purpose in these two districts. Water samples were collected in March and September 2003, representing the pre-monsoon and post-monsoon seasons, respectively. Water samples were analysed for almost all major cations, anions, dissolved heavy metals and turbidity. Parameters like sodium adsorption ratio, % sodium, residual sodium carbonate, total hardness, potential salinity, Kelley's ratio, magnesium ratio, index of base exchange and permeability index were calculated on the basis of chemical data. A questionnaire was also used to investigate perception of villagers on taste and odour. Comparison of the concentration of the chemical constituents with WHO (world health organization) drinking water standards of 2004 and various classifications show that present status of groundwater in Patiala is better for irrigation and drinking purposes except for a few locations with a caution that it may deteriorate in near future. In Muktsar, groundwater is not

suitable for drinking. Higher total hardness (TH) and total dissolved solids at numerous places indicate the unsuitability of groundwater for drinking and irrigation. Results obtained in this forms baseline data for the utility of groundwater. In terms of monsoon impact, Patiala groundwater shows dilution and flushing but Muktsar samples show excessive leaching of different chemical components into the groundwater leading to the enrichment of different anions and cations indicating pollution from extraneous sources. No clear correlation between the quality parameters studied here and perceived quality in terms of satisfactory taste response were obtained at electrical conductivity values higher than the threshold minimum acceptable value.

Keywords Drinking and irrigation utility · Groundwater · Muktsar · Patiala · Punjab · India

Introduction

The phenomenal human population growth has intensified pressure on each and every natural resource to produce adequate food and raw materials to meet the proportional demand (Smil 1999). With the advent of green revolution technologies, India has increased the consumption of fertilizer from 0.3 million metric tons in 1961–18.7 million metric tons in 2000, which resulted in a 170% increase in cereal production during the same period where as the increase in population nearly doubled (FAO 1996). During the next three decades, world population will increase by another 2 billion demanding a higher production of food. The food security can be achieved only through improvements in crop yields, which would require a 30% increase in fertilizer use. This increased fertilizer requirement has to

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be balanced against the environmental and human health concerns stemming from intensive fertilizer applications, particularly in fast developing and industrialized countries.

The World Health Organization (WHO) has repeatedly insisted that the single major factor adversely influencing the general health and life expectancy of a population in many developing countries is lack of ready access to clean drinking water (Nash and McCall 1995). Groundwater is important for human water supply and in Asia alone about 1 billion people are directly dependent upon this resource (Foster 1995). However, many groundwater exploitation schemes in developing countries are designed without due attention to quality issues. In recent years, in many parts of India especially in the arid- and semi-arid regions, due to the vagaries of monsoon and scarcity of surface water, dependence on groundwater has increased tremendously. In the view of international perspective of “<1,700 m³/person per year” as water stressed and “<1,000 m³/person per year” as water scarce, India is water stressed today and is likely to be water scarce by 2050 (Gupta and Deshpande 2004). It is projected that by 2020, the number of people living in water-scarce countries will increase from about 131 million to more than 800 million (Gardner-Outlaw and Engelman 1997).

India supports more than 16% of the world's population with only 4% of the world's fresh water resources (Singh 2003). The total area cultivated in India using groundwater has increased from 6.5 million hectare in 1951 to 35.38 million hectare in 1993 (GWREC 1997). In India, several studies have reported groundwater contamination by nitrate due to agricultural activities (Singh 1983; Hem 1985; Datta et al. 1997; Prasad 1998; Kumar et al. 2006a, b). The other study from India has been reported on the soil contamination due to irrigation water quality (Palaniswami and Ramulu 1994; Datta et al. 2000; Patel et al. 2004; Marechal et al. 2006). The study of fertilizer consumption data at the state level shows that consumption of plant nutrient per unit gross area is highest in Punjab at 158.9 kg/ha and lowest in Assam 14.6 kg/ha (Census of India 2004, Punjab). About 94% of the total sown area in Punjab is irrigated, out of which 61.6% is irrigated by tube wells and 38.3% by canals. However, uncontrolled extraction without commensurate recharge and heavy leaching of pollutants from pesticides and fertilizers to the aquifers has resulted in pollution of groundwater (Rajmohan and Elango 2005).

In general, colour and taste of the water are the two basic criteria for a consumer to decide the suitability of given water for drinking without considering other lethal chemical contaminations like arsenic, nitrate, fluoride and other heavy metal contaminations. It is therefore becomes essential to determine the present status of groundwater on the basis of its quality and thus its suitability for two major purposes viz. drinking and irrigation. There is no systematically and scientifically documented study on the groundwater quality in

these two districts is available except the unpublished reports from central groundwater board (CGWB 2001). Thus, this paper highlights the spatial and temporal variations in the groundwater quality in two extensively cultivated districts in Punjab and evaluates the suitability of groundwater for irrigation and drinking purpose for a sustainable agriculture and basic human needs. An effort has also been made to investigate relationship between perceived water quality by consumer and that of on the scale of measured scale. The result of the study will also be helpful in the sustainable management of groundwater resources.

Site description

The Patiala district

Physiography

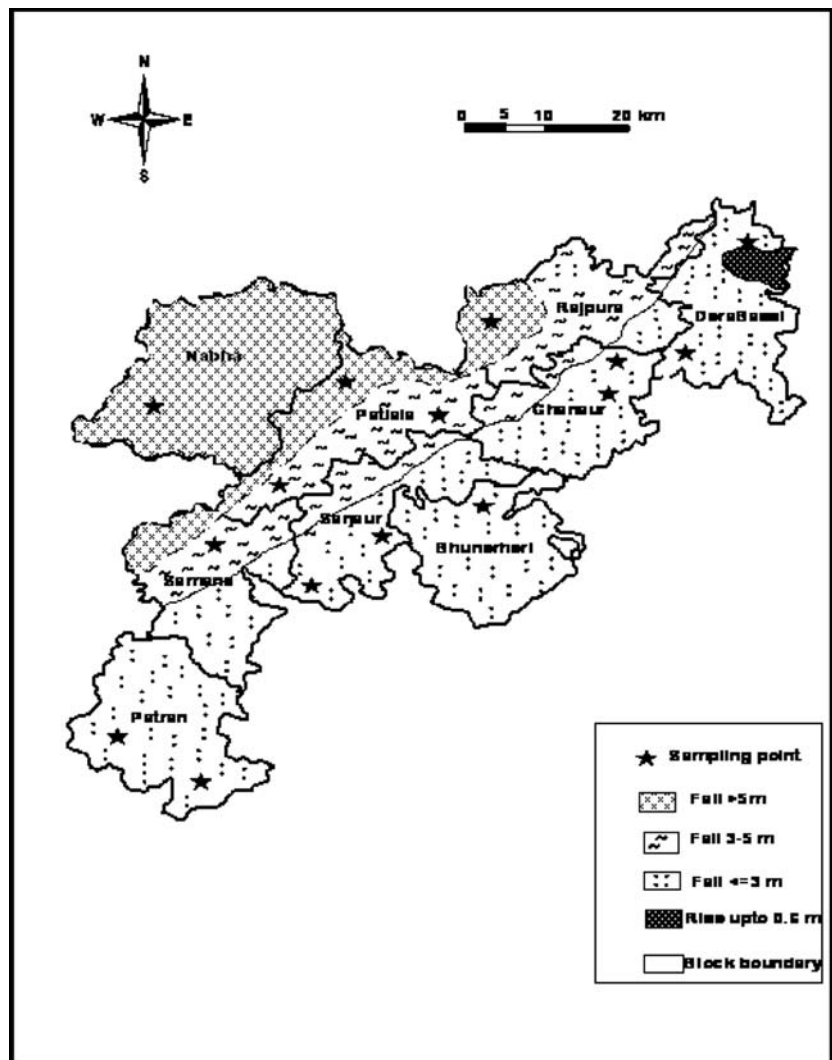
Patiala is located in the south eastern part of the Punjab state in the Malwa region. It lies approximately between latitude 20°49' to 30°47' North and longitude 75°58' to 76°54' East (Fig. 1). The district is subdivided into following sub micro regions on the basis of soils, topography, climate and natural vegetation: (a) Patiala plain with flat featureless plain having alluvial soils. The main soils are ochrept-orthents and ocharepts-psammets. Sheets of white powdery materials are found in some parts known as kollar or Reh. (b) Ghaggar flood plain in the eastern, south-eastern and southern parts of the Patiala district. The river Ghaggar, flows from northeast to southwest direction. The main soils are ustalfs-fluvents, Aquent-ochrepts and ustalfs-orthents. The elevation of this region varies from 230 to 256 m above mean sea level.

The annual average rainfall is 688 mm. On an average, there are 61 rainy days. The net area sown in the district is 84.2% which itself indicates how extensively cultivated area it is. 70.1% of its population is reportedly residing in rural areas. The annual rainfall being low, erratic, and seasonal there is necessity for the artificial irrigation (Census report 2004). Apart from the natural drainage line, the district also has three important canals- the Bhakra Main Line canal, the Nawana Branch, and the Ghaggar Link. These canals provide much needed irrigation water to the district. Before these canals were constructed, Patiala district was a water scarce area. These irrigation canals have helped to transform the parched fields into fertile, double-cropped lands.

Hydrogeology

This district is a part of Indo-Gangetic plain and composed of materials deposited by the rivers over the last 1.8 mil-

Fig. 1 Sampling locations with groundwater fluctuation noticed during 1984–2002 in Patiala district



lion years ago. The district has mean elevation of about 265 m. The land surface slopes in the north-east to south-east direction with a gentle gradient of about 0.8 m/km. The alluvial deposits are of heterogeneous character which consists of sandy clay, sand, clay, gravel, pebble and *kankar* deposited by the Ghaggar River. The major units occur in a definite pattern viz. (i) soft clay, slightly sandy (sandy clay), (ii) hard clay (locally known as *Chis*) and (iii) coarse greyish sand (Fig. 2).

The first unit of sandy clay occurs up to an average depth of 4.18 m, the second at 9 m and the third at 17.92 m. The marked variation in depth and the thickness of the units suggests the alluvium deposits of the area have been brought by nallas flowing from the Shiwalik Hills. The alluvium deposits have been responsible for the introduction of heterogeneity in the lithological column. The district is poor with regard to mineral wealth. However, Saltpeter (trade name for all the nitrates of Na, K and Ca) and *kankar* has been found in many places of districts.

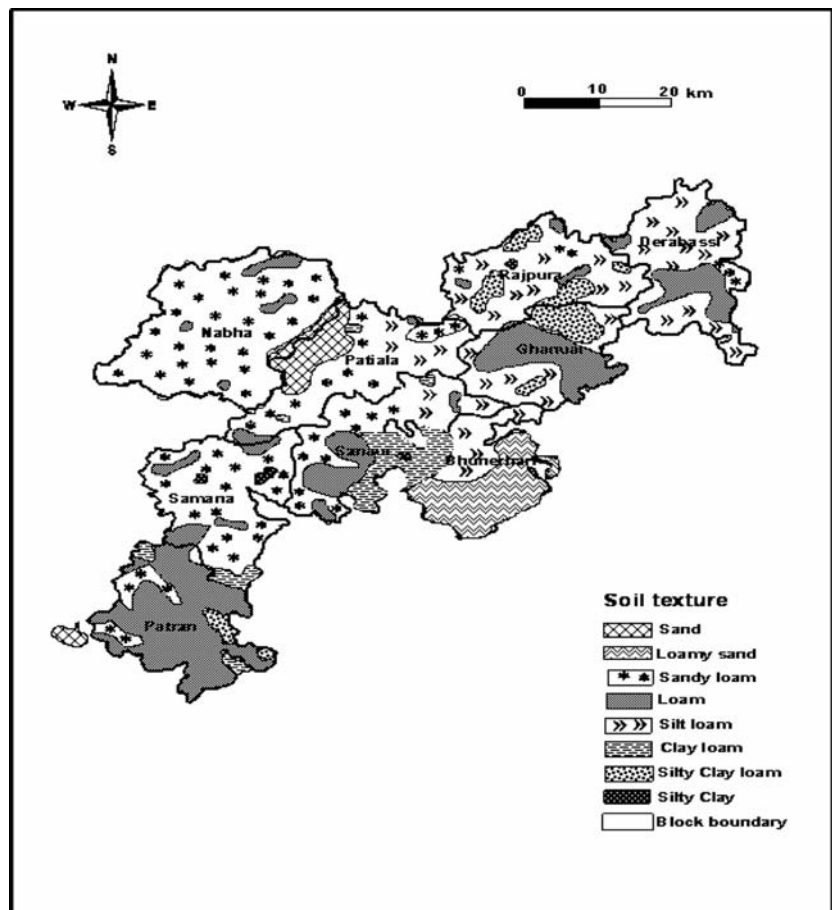
The alluvial deposits have rich groundwater potential, having shallow unconfined aquifers. Groundwater occurs both under phreatic and confined conditions. The aquifers in the area are constituted of silt and very fine sand. A tubewell at Dhappar constructed to a depth of 308.3 metres yields a discharge of 2680 LPM for a drawdown of 21 m (*Source: District Gazeteers, Patiala*). Groundwater movement in the district is from north-east to south-west. Out of total area of 3,762 km², nearly 60% of area faced 0–5 m of decline while rest of the part of the districts has registered 5 to 10 m of water level decline (Fig. 1) since June 1984 to June 2002 (Takshi and Chopra 2004).

Muktsar district

Physiography

Muktsar district, is located in the south-western part of Punjab and lies between north 29°54' 20" and 30°4' 20"

Fig. 2 General map for soil type of Patiala district



latitude and east $74^{\circ}15''$ and $74^{\circ}19''$ longitude. Geomorphologically, the area is a vast stretch of old and recent alluvium of Quaternary age as modified by orogenic processes associated with fluvial action. The area has been divided into two major geomorphic units, viz. Alluvial plain and Palaeo channels/Sand dune complexes (Fig. 3). Alluvial plain constitutes the major part of study area. This unit is formed by the alluvial deposits brought by Satluj River. These deposits consist of sand, silt, clay, and *kankar*. This unit is further subdivided into three sub units: (i) Upper alluvial plain composed of massive beds of clay and fine to coarse grained sand. The yellowish impervious clay/sticky clay locally known as *pandoo* occurs below the intermediate horizon of soil and *Kankar* and helps in confining the water under artesian conditions. (ii) Alluvial Plain with good moisture or water logged and (iii) Alluvial plain with salt encrustations consisting clay, sticky clay (*Pandoo*) and fine grained sand. The *Pandoo* helps in confining the water under artesian conditions, obstructing the drainage of the soil. This leads to the accumulation of sodium and magnesium salts and thus giving rise to salt encrustations on the surface and rendering the soil infertile. The Western Himalayas in the north and the Thar Desert in the south and southwest, mainly determines the climatic

conditions of Muktsar. There is no river flowing through the district. The soils in the district were largely developed on alluvium. The district has two types of soils, sierozem and desert soils. The net area sown is 84% of the total geographical area. This district is irrigated by two types of irrigation, surface irrigation by canals and groundwater irrigation by tube wells.

Hydrogeology

The area is underlain by the Indus alluvium of the quaternary age. The exploratory drilling in Indus basin also shows the presence of thick sandy aquifer zones with the intervening thin clay layers identifying it as one unified multi-aquifer system (Fig. 4). The pumping tests on different test wells have shown high permeability (15–25 m/day) indicating high potential aquifer systems. Below the thick alluvial sediments, different types of basement rocks have been encountered. The area has both confined and unconfined aquifers (CGWB Report 2001). Out of total area of 2,608 km², only 30% of the area in the districts faced 0–3 m of decline while rest of the part has registered up to 10 m of water level rise from June 1984 to June 2002 (Takshi and Chopra 2004).

Fig. 3 Sampling location and geomorphology of Muktsar district

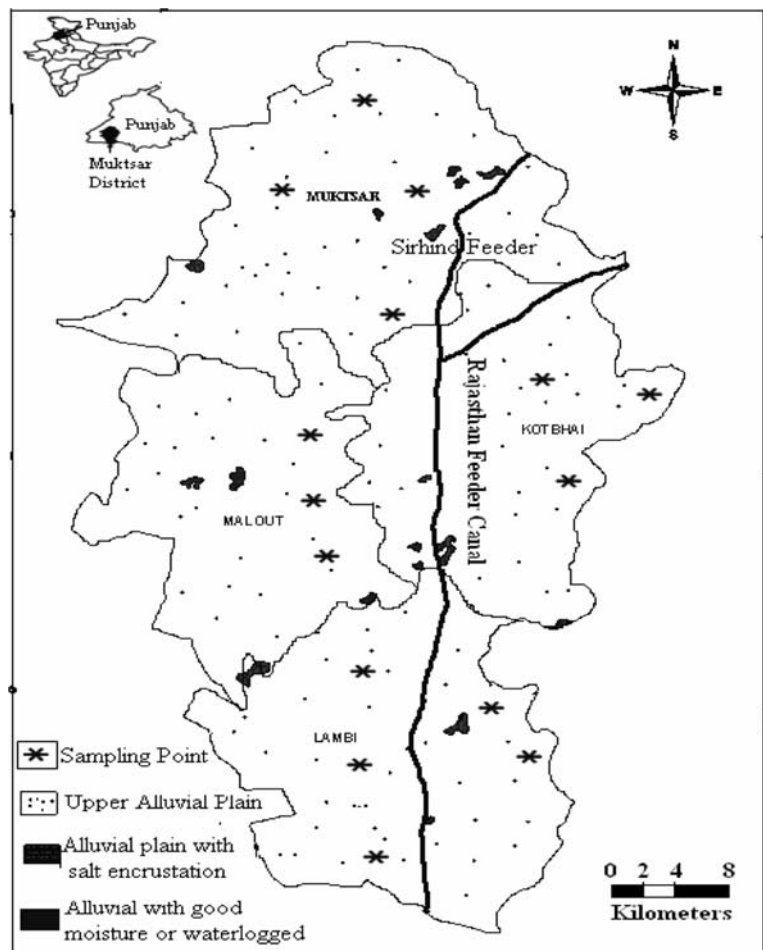
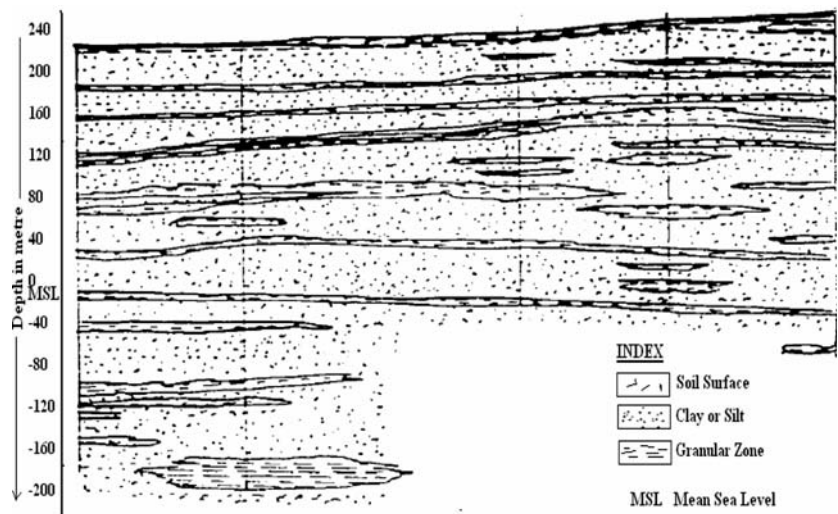


Fig. 4 Laterally extensive multiple aquifer system in Punjab area of Indus basin



Materials and methods

Initially, to understand the general variation in groundwater chemistry of the study area, a well inventory was carried out during February 2003, and electrical conductivity (EC) and pH were measured. A Garmin III global positioning system

(GPS) was used for location reading with the accuracy of 20 m. These data were used to select the representative tubewell and hand pumps for groundwater sampling. Sampled wells were selected to represent different geological formations as well as land-use pattern and different depths of the aquifer. Fifteen groundwater samples were collected

from each district in March 2003 (pre-monsoon) and same locations were again sampled in September 2003 (post-monsoon) to evaluate seasonal variations.

There water samples were collected in clean polyethylene bottles. At the time of sampling, bottles were thoroughly rinsed two to three times with groundwater to be sampled. In the case of bore wells and hand pumps, the water samples were collected after pumping for 10 min. This was done to remove groundwater stored in the well. In situ measurements included EC, pH, DO, ORP, temperature and bicarbonate which were measured using a portable field kit and titration respectively as per WHO (1996a, b) recommendations as these parameters change with the storage time. Sometimes, the turbidity was analysed on site or samples were collected, stored in cooler boxes and analysed the same day. Samples collected were brought to the laboratory and were filtered using 0.45 μm Millipore filter paper and acidified with nitric acid (Ultrapure Merck) for cation analyses and HBO_3 acid was used as preservative for nitrate analysis (Kumar 2004). For anion analyses, these samples were stored below 4°C. Major cations like Ca^{2+} , Mg^{2+} , Na^+ and K^+ were determined on flame photometer, and heavy metals were determined using Shimadzu AAS. The chemical analysis was carried out as per standard procedure given in APHA (1995). Fluoride was determined using Thermo-Orion Benchtop Ion Selective Electrode. Nitrate determination was performed by using the brucine method. The analytical precision for ions measurements was determined by calculating the ionic balance error. Apart from the collection and analysis of water samples, other data and information about study area were collected from the Central Ground Water Board (CGWB), New Delhi.

A simple questionnaire, consisting five questions in yes and no format, was used to investigate perceptions of villagers of taste and odour. Randomly ten people were interviewed on each location who are supposed to be regular consumer of that particular pump. The questionnaire also included a provision for the research team's observations on the colour of water, general state of water point and location. An investigation on the variability of measurements taken for the same parameter but using different instruments was carried out and in all the cases, deviations in measurements using different instruments did not exceed 5%, which was deemed negligible for practical purposes.

Results and discussions

Groundwater chemistry

Understanding the quality of groundwater with its temporal and seasonal variation is important because it is the factor that determines suitability for drinking, domestic, agricul-

tural and industrial purposes. The analytical results, computed values and the statistical parameters like minimum, maximum, mean, median and the standard deviation values of water samples of Patiala and Muktsar are given in Tables 1 and 2, respectively.

The groundwater is alkaline in nature in both the districts. In Patiala, pH of the pre-monsoon sample ranged from 7.1 to 7.6 with an average value of 7.3, while in the post-monsoon a slight increase was observed and ranged from 7.3 to 8.1 with the average of 7.6. In comparison to Patiala, the groundwater of Muktsar is slightly more alkaline in nature as evident from the average as well as range value of pH. Thus in both the districts, dilution due to influx of rainwater of lower alkalinity has affected the pH of groundwater. An increase of pH in the post-monsoon suggests that dissolution has been enhanced due to high interaction between soil and rainwater (Subramanian and Saxena 1983). EC of groundwater of Patiala ranged from 430 to 1,960 and 239–1,496 $\mu\text{S}/\text{cm}$ in the pre- and the post-monsoon, respectively. The higher average value of EC in the pre-monsoon suggests the enrichment of salt due to evaporation effect in the pre-monsoon followed by subsequent dilution through rainwater. Like pH, EC is also higher in Muktsar than that of Patiala, perhaps because of additional leaching derived from sand dunes, anthropogenic sources and intense agricultural activities compared to Patiala. Very high standard deviation in EC for Muktsar suggests local variation in point sources, soil type, multiple aquifer system and other agriculture related activities in the area. Alkalinity of water is the measure of its capacity for neutralization. Bicarbonate represents the major sources of alkalinity. Bicarbonate is slightly higher in the post-monsoon period indicating the contribution from carbonate weathering process. There was a slight variation in seasonal and spatial distribution and are very significant at certain locations, HCO_3^- was high due to contribution from carbonate lithology. Higher Cl_3^- in Muktsar confirms the anthropogenic sources are more in Muktsar compare to Patiala. In general, most of the natural waters, SO_4^{2-} is found in smaller concentrations than Cl^- . In Patiala SO_4^{2-} ranged from 10.3 to 202.7 mg/l in pre-monsoon and 4.5–97.2 mg/l in post-monsoon. In Muktsar it ranged from 22 to 903 mg/l in pre-monsoon and 42–3050 mg/l in post-monsoon. This indicates addition of sulphate by the breakdown of organic substances of weathered soils, sulphate leaching, from fertilizers and other human influences (Miller 1979; Craig and Anderson 1979; Singh 1994).

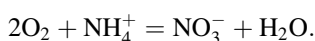
The dominant nutrients in the groundwater are in the following order $\text{NO}_3^- > \text{H}_4\text{SiO}_4 > \text{PO}_4^{3-}$. The concentration of silica in groundwater samples did show some seasonal fluctuations especially in Muktsar. The existence of alkaline environment enhances the solubility of silica and it reveals secondary impact of silicate weathering. The

Table 1 Summary statistics of chemical constituents of groundwater in Patiala districts with % of sample beyond permissible limit (PL) and values in parenthesis are % of sample beyond desirable limit (DL) of the WHO drinking water standard

Parameter	Units	Minimum		Maximum		Average		Median		Std. deviation	
		Pre-monsoon	Post-monsoon	Pre-monsoon	Post-monsoon	Pre-monsoon	Post-monsoon	Pre-monsoon	Post-monsoon	Pre-monsoon	Post-monsoon
pH	–	7.10	7.32	7.62	8.13	7.33	7.61	7.32	7.59	0.18	0.25
TDS	mg/l	245	158	12.5	985	646	551.8	572	645	306	264.21
EC	μS/cm	430	239	1,960	1,496	1022	792.13	970	383.14	453.2	750
Na ⁺	mg/l	2.40	3.03	101.84	95.58	45.54	41.03	50.97	34.42	30.1	35.29
K ⁺	mg/l	2.5	3.63	30.87	10.9	13.17	6.11	11.95	6.34	9.9	2.24
Ca ²⁺	mg/l	20.2	12.96	142.2	113.84	63.43	66.15	46.85	64.98	36.89	37.11
Mg ²⁺	mg/l	15.8	19.99	119.2	57.4	53.62	49.28	52.4	54.86	34.94	11.65
HCO ₃ ⁻	mg/l	156	115	670	704	379.20	326	375	171.5	142.80	306
Cl ⁻	mg/l	4.55	28.20	625	674.31	130.27	171.08	103.94	93	153.23	198.91
SO ₄ ²⁻	mg/l	10.33	4.50	202.7	97.2	38.25	46.15	22.01	37.3	48.2	26.1
SiO ₂	mg/l	18	20	44.52	51.33	3.42	33.75	32.01	35.29	9.68	10.29
PO ₄ ³⁻	mg/l	BD	BD	0.09	0.06	0.02	0.01	0.02	0.01	0.03	0.006
NO ₃ ⁻	mg/l	12	16.62	106	120.03	49.58	54.49	45.60	45.09	27.13	29.15
F ⁻	mg/l	0.17	0.06	0.66	0.54	0.34	0.26	0.33	0.257	0.15	0.14
Fe	mg/l	0.03	BD	4.01	0.43	1.46	0.15	1.11	0.11	1.32	0.13
Zn	mg/l	BD	BD	3.8	1.77	0.35	0.33	0.08	0.15	0.96	0.54
Mn	mg/l	0.01	0.02	0.3	0.19	0.16	0.09	0.16	0.09	0.09	0.05
Cu	mg/l	BD	0.12	1.94	0.81	0.23	0.33	0.13	0.26	0.48	0.21
T.H	mg/l	116.3	140	715	523.75	381.7	370.7	371.65	394	209.87	122.98
SAR	–	0.11	0.09	4.19	4.5	1.63	1.37	1.81	1.25	1.22	1.29
RSC	meq/l	-9.05	-7.94	5.76	6.98	-1.15	-2.0	-0.09	-1.75	4.79	3.88
%Na	%	4.73	2.79	53.4	55.54	25.54	19.69	22.69	19.1	17.24	15.14
PI	%	20	21.31	10	82.27	55	45.79	52	38.85	26	18.47
CAI-1	–	-39.63	-0.65	0.82	0.86	-2.89	0.44	0.2	0.69	10.32	0.53
CAI-2	–	-0.62	-0.21	1.73	2.39	0.19	0.44	0.03	0.23	0.56	0.76
Mg/Ca	–	0.62	0.67	4.6	6.11	1.51	1.82	1.41	1.13	0.93	1.44
Kelly's ratio	–	0.03	0.02	1.06	1.22	0.37	0.28	0.28	0.22	0.35	0.31
Magnesium ratio	–	38.08	40.41	82.14	85.94	56.89	58.48	58.46	53.03	10.46	13.96

BD below detection limit

concentration of nitrogen in groundwater is derived from the biosphere (Saleh et al. 1999). Nitrogen is originally fixed from the atmosphere and then mineralized by soil bacteria into ammonium. The main source of nitrate in the study area is the application of fertilizer in the irrigation water. The common fertilizer applied is (NH₄)₂SO₄. Through nitrification processes in the presence of oxygen, ammonia is transferred to nitrates, according to the reaction:



Greater mineralization is generally associated with higher nitrate concentration. The high nitrate concentration may occur due to leaching of NO₃⁻ from fertilizers and biocides

during the irrigation of agriculture land. The average value of nitrate in both the districts was higher for the post-monsoon due to the monsoon effect. As the small amount of fertilizer applied to soils (mostly Aridisols) that remain dry almost all the year, do not constitute a major threat for nitrate pollution of groundwater, except possibly when soils are irrigated. Besides of high rainfall, irrigation is becoming increasingly available to farmers in this part of humid tropics, which releases substantial leaching of N. The PO₄³⁻ in the study area was very low, may be because of phosphate adsorption by soils as well as its limiting factor nature due to which whatever PO₄³⁻ is applied to the agricultural field is used up by the plants. Since the plantation is mostly wheat in the area which consumes more PO₄³⁻ is also a supporting fact for the finding. Bedrock containing fluoride minerals is

Table 2 Summary statistics of chemical constituents of groundwater in Muktsar districts with % of sample beyond permissible limit (PL) and values in parenthesis are % of sample beyond desirable limit (DL) of the WHO drinking water standard

Parameter	Units	Minimum		Maximum		Average		Median		Std. deviation	
		Pre-monsoon	Post-monsoon	Pre-monsoon	Post-monsoon	Pre-monsoon	Post-monsoon	Pre-monsoon	Post-monsoon	Pre-monsoon	Post-monsoon
pH	–	7.12	7.23	8.21	8.74	7.56	7.77	7.55	7.82	0.33	0.41
TDS	Mg/l	302	324	3643	6,970	1,031.7	2,225.6	645	1,301	1,029.8	1,919
EC	μS/cm	530	500	5,520	7,580	1,645	2,774	1,080	1,840	1,552	2,174.7
Na ⁺	mg/l	42	24.14	4,025	6,060	354.7	478.98	99.15	90.7	1,269	1,544
K ⁺	mg/l	7.89	3.8	120.3	99.21	25.55	21.32	16.92	13.95	34.63	24.44
Ca ²⁺	mg/l	23	25.2	327	122.22	108	70.9	83.7	78.83	91	28.59
Mg ²⁺	mg/l	59.21	52.9	228	63.72	110.71	58.64	89.6	59.54	57.27	3.34
HCO ₃ ⁻	mg/l	218	217	773	963	482.47	501.7	463	471	176.94	209.84
Cl ⁻	mg/l	16.83	58	625.3	4,466	178	1,270.6	118	635	202	1,498
SO ₄ ²⁻	mg/l	22	42	903	3,050	333	393.9	293	148	305	756.5
SiO ₂	mg/l	16.02	22.02	82.05	45.28	38.77	32.97	35.3	31.25	18.6	7.26
PO ₄ ³⁻	mg/l	BD	0.002	0.09	0.06	0.03	0.01	0.02	0.003	0.03	0.02
NO ₃ ⁻	mg/l	7.49	15.02	120	120	62	64.48	64.3	62.25	38.27	30.52
F ⁻	mg/l	0.04	0.02	1.61	0.75	0.89	0.2	0.838	0.14	0.43	0.18
Fe	mg/l	0.16	0.11	0.9	47.35	0.5	0.76	0.456	0.416	0.25	1.09
Zn	mg/l	0.03	BD	3.8	0.81	0.92	0.39	0.63	0.32	1.16	0.25
Mn	mg/l	0.01	0.02	0.62	1.32	0.15	0.17	0.04	0.057	0.21	0.33
Cu	mg/l	BD	0.16	0.46	0.65	0.11	0.41	0.04	0.52	0.16	0.17
TH	mg/l	358	285.88	1,250	552.3	731.07	421	634.5	435	301.3	75.23
SAR	–	1.03	0.65	70.72	168.15	6.77	13.51	2.36	2.77	22.13	42.73
RSC	meq/l	-16.93	-4.99	4.43	6.05	-6.33	-0.14	-7.95	0.256	6.13	3.25
% Na	%	12.75	14.56	87.73	96.41	29.95	36.73	26.21	33.07	21.55	18.56
PI	%	20.9	40.35	89.5	97.86	41.25	55.93	19	51.92	41	14.24
CAI-1	–	-52.18	-1.85	0.63	0.98	-4.82	0.35	-4.11	0.70	16.54	0.83
CAI-2	–	-11.8	-4.36	1.51	7.75	-0.71	1.18	-0.22	0.79	3.91	2.6
Mg/Ca	–	0.5	0.81	10.87	3.54	2.57	1.71	1.95	1.25	3.09	0.94
Kelly's ratio	–	0.13	0.10	7.14	26.83	0.76	2.20	0.32	0.45	2.25	6.82
Magnesium ratio	–	33.35	44.68	91.58	77.46	63.74	59.65	66.08	55.63	17.34	10.81

BD below detection limit

generally responsible for high concentration of fluoride in groundwater (Handa 1975; Wenzel and Blum 1992). The concentration of fluoride in groundwater of Patiala varied between 0.2 and 0.7 mg/l during March 2003 with an average value of 0.5 mg/l and median 0.3 mg/l. The concentration was slightly lower during September 2003, ranging between 0.06 and 0.5 mg/l with an average of 0.3 mg/l. In Muktsar, Fluoride was higher in pre-monsoon but less in post-monsoon than that of Patiala.

In Patiala, dominant cations are in the order of Ca > Mg > Na > K while in Muktsar order was Na > Ca > Mg > K. Not much seasonal variation has been observed in cations concentration in Patiala but in case of Muktsar, there was a clear seasonal variation both in

minimum and maximum concentrations. This is due to different soil types in the area. In spite of greater resistance of potassium silicate to weathering, ions are released during weathering but they seem to be used up in the formation of secondary minerals. The abnormal concentration of potassium at few places is due to urban pollution and fertilizer leaching.

Correlation analysis

A correlation analysis is a bivariate method, which simply exhibits how well one variable predicts the other. In this study, the relationship between various elements has

Table 3 Correlation matrix of chemical constituents of groundwater in Patiala districts

	pH	EC	TDS	Na ⁺	K ⁺	Ca ²⁺	Mg ²⁺	Cl ⁻	HCO ₃ ⁻	SO ₄ ²⁻	SiO ₂	NO ₃ ⁻	F ⁻	PO ₄ ³⁻	Cu	Fe	Zn	Mn
(a) Pre-monsoon																		
PH	1.00																	
EC	-0.63	1.00																
TDS	-0.61	0.99	1.00															
Na ⁺	0.31	-0.24	-0.20	1.00														
K ⁺	0.10	-0.09	-0.07	0.46	1.00													
Ca ²⁺	-0.01	0.19	0.14	-0.15	0.14	1.00												
Mg ²⁺	0.19	0.22	0.19	0.08	0.02	0.54	1.00											
Cl ⁻	0.27	0.01	0.00	0.30	0.01	0.13	0.75	1.00										
HCO ₃ ⁻	0.09	0.04	0.11	0.28	0.47	0.16	-0.09	0.08	1.00									
SO ₄ ²⁻	-0.09	0.67	0.62	-0.33	-0.10	0.20	0.32	0.08	-0.13	1.00								
SiO ₂	-0.29	0.21	0.25	-0.03	0.15	0.32	0.16	-0.21	0.19	-0.15	1.00							
NO ₃ ⁻	0.19	-0.20	-0.20	-0.04	-0.15	0.60	0.44	0.13	0.01	-0.27	0.47	1.00						
F ⁻	0.38	-0.20	-0.19	0.41	0.36	-0.15	0.38	0.58	0.16	-0.02	-0.12	0.06	1.00					
PO ₄ ³⁻	0.06	-0.40	-0.42	0.01	-0.36	-0.06	0.13	0.37	-0.24	-0.29	0.06	0.15	0.00	1.00				
Cu	-0.33	0.19	0.16	0.12	0.04	-0.20	-0.34	0.00	0.02	-0.14	-0.22	-0.39	-0.33	0.09	1.00			
Fe	0.14	0.22	0.19	-0.21	0.04	0.06	-0.07	-0.13	-0.09	0.37	-0.41	-0.30	-0.40	-0.46	0.45	1.00		
Zn	0.44	-0.28	-0.26	0.44	-0.03	-0.10	0.57	0.91	-0.01	-0.11	-0.28	0.06	0.60	0.46	-0.13	-0.25	1.00	
Mn	0.27	-0.14	-0.21	-0.42	-0.03	0.19	-0.02	-0.32	-0.50	0.41	-0.26	0.03	0.03	-0.18	-0.39	0.18	-0.29	1.00
(b) Post-monsoon																		
PH	1.00																	
EC	-0.15	1.00																
TDS	-0.22	0.97	1.00															
Na ⁺	0.00	-0.16	0.00	1.00														
K ⁺	-0.16	0.48	0.45	0.12	1.00													
Ca ²⁺	-0.56	-0.05	0.05	0.12	-0.24	1.00												
Mg ²⁺	-0.55	0.56	0.61	-0.01	0.53	0.47	1.00											
Cl ⁻	-0.21	-0.13	-0.04	0.42	-0.05	0.43	0.22	1.00										
HCO ₃ ⁻	0.11	0.49	0.49	0.21	0.35	-0.25	0.27	0.02	1.00									
SO ₄ ²⁻	-0.11	0.57	0.55	0.03	0.06	-0.01	0.14	-0.21	0.64	1.00								
SiO ₂	-0.36	-0.02	-0.06	-0.03	-0.03	0.46	0.14	0.03	-0.41	0.05	1.00							
NO ₃ ⁻	-0.02	0.18	0.25	0.08	0.02	0.53	0.22	0.08	-0.19	-0.01	0.50	1.00						
F ⁻	-0.09	-0.24	-0.23	-0.15	-0.30	0.54	0.28	0.42	-0.20	-0.12	0.43	0.36	1.00					
PO ₄ ³⁻	0.18	-0.16	-0.04	0.27	-0.05	0.26	0.17	-0.12	-0.35	-0.30	0.11	0.50	0.29	1.00				
Cu	-0.19	0.26	0.25	0.04	0.73	-0.10	0.38	-0.29	-0.11	-0.28	-0.06	0.08	-0.44	0.20	1.00			
Fe	-0.25	0.06	0.14	0.22	-0.02	0.34	0.14	-0.09	-0.28	0.15	-0.03	0.12	-0.12	0.39	0.30	1.00		
Zn	0.71	0.00	-0.07	0.26	-0.14	-0.42	-0.49	-0.05	0.35	0.20	-0.20	-0.02	-0.15	-0.15	-0.21	-0.23	1.00	
Mn	-0.09	-0.11	-0.05	-0.12	-0.11	-0.30	-0.09	0.24	0.03	-0.20	-0.42	-0.34	0.08	-0.10	-0.31	-0.18	-0.26	1

been studied using the Spearman rank coefficient which is based on the ranking of the data and not their absolute values (Kurumbein and Graybill 1965; Kumar et al. 2006a, b).

The correlation matrices for 18 variables were prepared for both pre- and post-monsoon periods for each district using SPSS. In Patiala, the result of correlation matrix in pre-monsoon (Table 3) is very much different from that in post-monsoon (Table 3), which indicated a significant impact of monsoon in the area. Besides the strong correlation between

EC and total dissolved solids (TDS), a strong correlation ($r=0.7$) also existed between EC-SO₄ and Cl-Mg. pH also showed impact of monsoon as it exhibited negative correlation with most of the variables, being different from pre-monsoon. Besides the constant relation between EC-SO₄ in both the seasons, Na did not show any significant relation with any parameter during both the seasons. Nitrate shown good correlation with PO₄ in post-monsoon which was not the case in pre-monsoon. PO₄ showed opposite correlation

with Fe to that with Zn. Particularly, Zinc not only showed relatively strong correlation with Cl but also had moderate correlation with Mg, F, Na and PO₄. These correlations do indicate some impact of agricultural activities in the study area. Among the heavy metals, Cu-Fe exhibited good correlation followed by the pairs such as Mn-Fe, Mn-Zn and Fe-Zn, which did show relatively lower correlations after monsoon due to dilution effect.

In contrast to Patiala groundwater, Muksar showed a different nature like stronger negative correlation between NO₃ and F, a moderate to the strong correlation of Na with some of the variables. Cl and HCO₃ played a major role than SO₄ (Table 4). But, in both the districts SO₄ showed a good relationship with Fe during pre-monsoon, but in Patiala it was negatively correlated. This may be due to use of some chemicals for agricultural purposes. Overall, in

Table 4 Correlation matrix of chemical constituents of groundwater in Muksar districts

	pH	EC	TDS	K ⁺	Na ⁺	Ca ⁺	Mg ⁺	HCO ₃ ⁻	Cl ⁻	SO ₄ ²⁻	SiO ₂	PO ₄ ³⁻	NO ₃ ⁻	F ⁻	Cu	Fe	Zn	Mn
(a) Pre-monsoon																		
pH	1.00																	
EC	0.09	1.00																
TDS	0.07	0.99	1.00															
K ⁺	-0.07	-0.14	-0.13	1.00														
Na ⁺	-0.41	-0.21	-0.18	-0.16	1.00													
Ca ²⁺	-0.38	-0.18	-0.16	0.09	0.77	1.00												
Mg ²⁺	-0.15	0.62	0.62	-0.21	-0.06	-0.08	1.00											
HCO ₃ ⁻	-0.20	0.14	0.14	0.07	0.49	0.48	-0.01	1.00										
Cl ⁻	-0.07	0.12	0.20	-0.16	-0.07	-0.35	0.25	-0.33	1.00									
SO ₄ ²⁻	0.20	-0.17	-0.19	0.07	-0.30	0.06	-0.33	0.07	-0.33	1.00								
SiO ₂	-0.42	-0.09	-0.07	0.06	-0.08	-0.04	0.50	-0.06	0.48	-0.17	1.00							
PO ₄ ³⁻	-0.07	0.14	0.14	-0.09	-0.21	-0.28	0.10	-0.39	-0.09	-0.36	-0.27	1.00						
NO ₃ ⁻	-0.17	-0.37	-0.37	-0.20	0.09	-0.25	-0.12	-0.29	0.16	0.11	-0.10	0.22	1.00					
F ⁻	0.44	0.18	0.14	-0.25	-0.23	-0.24	0.07	0.03	-0.17	-0.20	-0.15	-0.10	-0.50	1.00				
Cu	0.19	0.51	0.53	-0.25	-0.19	-0.41	0.19	-0.32	0.60	-0.03	-0.10	-0.03	0.10	0.09	1.00			
Fe	-0.06	0.06	0.03	-0.07	-0.40	-0.20	-0.26	0.02	-0.24	0.58	-0.15	0.20	0.01	-0.01	0.15	1.00		
Zn	-0.40	0.22	0.21	-0.12	-0.12	-0.08	0.39	-0.26	0.43	0.04	0.54	-0.20	0.20	-0.27	0.35	0.08	1.00	
Mn	0.17	0.31	0.32	-0.25	-0.10	-0.33	-0.19	0.01	0.40	-0.12	-0.37	-0.03	0.12	0.19	0.57	-0.06	0.04	1.00
(b) Post-monsoon																		
pH	1.00																	
EC	-0.25	1.00																
TDS	-0.37	0.56	1.00															
Na ⁺	0.65	0.18	0.07	1.00														
K ⁺	0.14	-0.15	-0.27	-0.05	1.00													
Ca ²⁺	0.35	0.36	-0.04	0.23	0.03	1.00												
Mg ²⁺	0.32	-0.16	0.08	0.19	0.28	0.16	1.00											
Cl ⁻	0.33	0.10	-0.03	0.59	-0.02	0.31	-0.14	1.00										
HCO ₃ ⁻	0.49	0.10	-0.05	0.60	-0.20	0.27	0.44	0.46	1.00									
SO ₄ ²⁻	-0.17	-0.13	-0.16	0.09	-0.10	0.04	-0.35	0.57	0.15	1.00								
SiO ₂	-0.43	0.30	0.61	-0.42	-0.06	-0.04	0.17	-0.18	-0.27	-0.17	1.00							
NO ₃ ⁻	0.43	0.17	-0.11	0.51	0.06	0.22	0.19	0.60	0.28	0.18	0.03	1.00						
F ⁻	-0.01	0.06	-0.07	-0.20	0.10	0.25	0.23	-0.28	0.31	-0.15	-0.01	-0.56	1.00					
PO ₄ ³⁻	0.02	-0.09	-0.18	-0.07	0.12	0.37	-0.17	-0.14	-0.36	-0.20	-0.19	-0.33	-0.06	1.00				
Cu	0.05	-0.41	-0.12	-0.25	0.12	-0.01	0.22	-0.19	-0.16	0.16	0.22	0.03	0.04	-0.15	1.00			
Fe	0.37	-0.27	-0.23	-0.15	-0.35	0.39	-0.05	-0.08	-0.13	-0.17	-0.13	0.06	-0.18	0.31	0.20	1.00		
Zn	-0.26	-0.10	0.37	-0.15	-0.36	-0.04	0.45	-0.13	0.28	-0.02	0.40	-0.17	0.14	-0.10	0.44	-0.01	1.00	
Mn	0.03	0.24	0.12	-0.09	-0.20	0.13	-0.19	0.45	0.08	-0.09	0.32	0.42	-0.23	-0.24	-0.15	0.23	0.04	1

Muksar EC–TDS, SiO₄–TDS, Na–Cl, Na–HCO₃, Na–NO₃, NO₃–F and Cl–SO₄ exhibited correlation of more than 0.5 while Mg–HCO₃, Cl–HCO₃ and Zn–Cu pairs had a correlation from 0.4 to 0.5 in post-monsoon. While in pre-monsoon, correlation was more than 0.5 exhibited by Mg– SiO₂, Na–Cl, Na–HCO₃, Cl–Cu and Na–Ca pairs. Among the pairs like Fe–Na, Mg–Zn, PO₄–HCO₃, Cu–Mn and Fe–NO₃ correlation was more than 0.4. pH and F exhibited a negative correlation with most of the variables and SiO₂ exhibited no significant correlation with any one of the variables in the matrices.

Graphical representation of hydrochemical data

The geochemical evolution of groundwater can be understood by plotting the concentrations of major cations and anions in the Piper (1944) tri-linear diagram. Aquachem software was used for plotting the Piper diagram. The piper plot of Patiala (Fig. 5) showed that almost all the groundwater samples of September 2003 fell in the category of Ca–HCO₃ type of water which indicated sufficient recharge from fresh water. But in pre-monsoon although most of the samples fall in same category as in post-monsoon but a number of samples also fall in the category of mixed Ca–Mg–Cl type of water (Fig. 5). Some samples are also represented Ca–Cl types. It is clearly evident from the plot that alkaline earth metals (Ca²⁺ and Mg²⁺) significantly exceed the alkalis (Na⁺ and K⁺) and weak acids

(HCO₃⁻ and CO₃²⁻) dominated strong acids (Cl⁻ and SO₄²⁻). The groundwater had secondary salinity, as indicated by the carbonate hardness. In the study area, the alkaline earths had a higher concentration than bicarbonate which indicated exchange of Na⁺ ion from the alkaline earths and the water as base exchanged hardened water.

Piper plot of Muksar showed much variation in water type than Patiala (Fig. 6). The plot shows that most of the groundwater samples of March 2003 fall in the region of mixed Ca–Mg–Cl type of water and in post-monsoon most of them fall in the region of Ca–Cl type water. In both the seasons some samples also represented Ca–HCO₃ and Na–Cl type water. In pre-monsoon we did have one sample in the Na–HCO₃ domain, but we did not have any sample in the mixed Ca–Na–HCO₃ domain in both the seasons. We did have same pattern for cations in Patiala with some exceptions but for anions, the situation was different in Muksar. We had HCO₃ and SO₄ as dominant anions in pre-monsoon but Cl became dominant after monsoon indicating a clear shift of water type in the post-monsoon period.

Drinking water quality

Groundwater is the main source of safe and reliable drinking water in rural areas in both the districts of Punjab. Various parameters such as nitrate are important for health but total coliforms, conductivity, sodium, calcium, magnesium and fluoride may be regarded as the critical five

Fig. 5 Piper plot for Patiala for pre-monsoon and post-monsoon

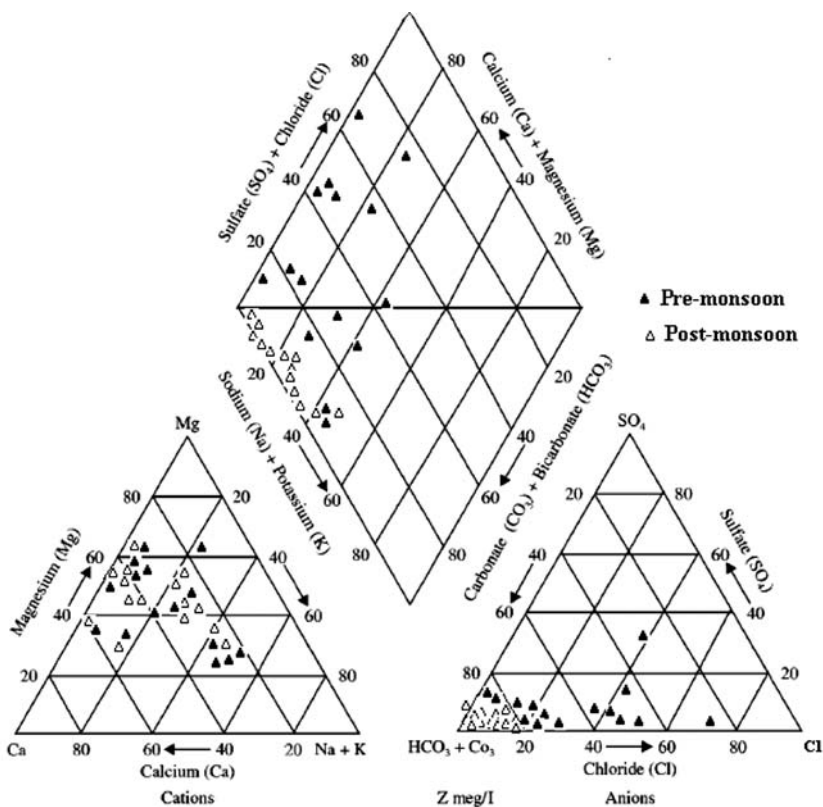
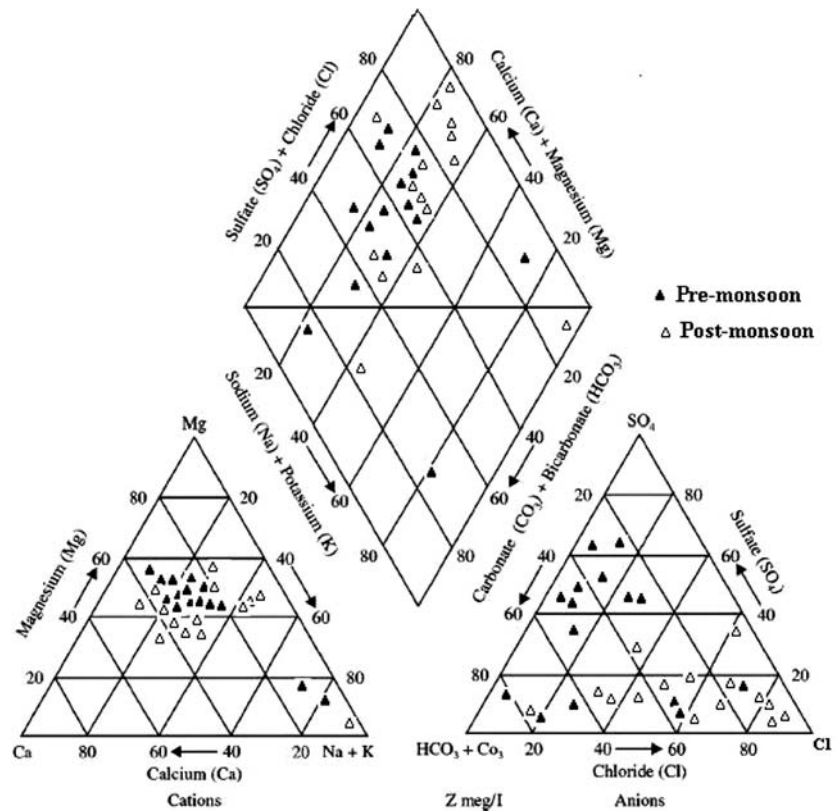


Fig. 6 Piper plot for Muktsar for pre-monsoon and post-monsoon



determinants for most developmental studies. According to WHO (1996a, b), the physical parameters that are likely raise complaints from end users are colour, taste, odour, temperature, and turbidity. WHO (1996a, b) suggests that total dissolved solids (TDS) greater than 1,000 mg/l result in taste complaints while low pH causes corrosion but high pH results in taste complaints. The palatability of drinking water rated by panels of tasters in relation to its TDS level is as follows: excellent, less than 300 mg/l; good, between 300 and 600 mg/l; fair, between 600 and 900 mg/l; poor, between 900 and 1,200 mg/l; and unacceptable, greater than 1,200 mg/l (WHO 1996a, b). Water with extremely low concentrations of TDS may also be unacceptable because of its flat, insipid taste. The most commonly used method of determining TDS in water supplies is the measurement of specific conductivity (WHO 1996a, b). Conductivity measurements are converted to TDS values by multiplying EC by a factor that varies with the type of water. Sawyer et al. (1994) suggest a range of 0.6–0.9 for this factor.

It is because this background coupled with the logistic, economic aspects and available time for the study that only common physical parameters like pH, temperature, turbidity, dissolved oxygen, conductivity together with some major cations and anions were selected, as they generally have a direct relationship with perceived acceptability of water quality by consumers. Consumer perceptions were

investigated by their response to a questionnaire, which included questions on taste, odour and perceived clarity of water. The relationship between measured and perceived water quality was investigated. No detailed investigations on the geological systems and possible effects on quality were done.

Relationship between perceived water quality and measured water quality

The analytical results of physical and chemical parameters of groundwater were compared with the standard guideline values recommended by the World Health Organisation (WHO 1996a, b, 2004) for drinking and public health purposes (Table 5). The table shows the most desirable limits and maximum allowable limits of various parameters. In general, objectionable taste and unclear colour perceptions were common for the threshold minimum values.

Taste and conductivity WHO (1996a, b) suggests a threshold limit of 1,000 mg/l for TDS, which should correspond to about 1,380 $\mu\text{S}/\text{cm}$ as explained above. In all districts the threshold EC value for taste objections was lower than the derived threshold EC of 1,380 $\mu\text{S}/\text{cm}$. Taste can also be a problem even if the TDS concentration is lower than the threshold value especially when the

Table 5 Different guidelines values for the drinking water with the percentage of sample beyond permissible limit (PL) and the resulting health implications

Parameter	WHO standard (1994, 2004)		ISO:10500: 1991 standard		% of sample exceeding PL ^a						Health implications	
	Desirable limit (DL)	Maximum permissible limit (PL)	Patiala			Muktsar			Post-monsoon			
			DL	PL	Pre-monsoon	Post-monsoon	Pre-monsoon	Post-monsoon				
PH	7–8.5	9.2	6.5–8.5	No relax	–	–	–	–	–	–	–	Taste
EC (µS/cm)	500	1,400	500	1,000	26.6 (60)	6.6 (60)	20 (60)	46 (60)	46 (60)	20 (100)	6.6	Gastro-intestinal irritation
TH (mg/l)	100	500	300	600	40 (96)	13 (100)	86	20 (100)	20 (100)	6.6 (66)	–	Scale formation
Na ⁺ (mg/l)	–	200	–	–	–	–	–	–	–	–	–	Scale formation
Ca ²⁺ (mg/l)	75	200	75	200	0 (50)	–	6.6 (66)	–	–	–	–	Scale formation
Mg ²⁺ (mg/l)	50	150	30	100	0 (70)	0 (70)	20 (93)	100	100	–	–	Encrustations in water supply structure
Cl ⁻ (mg/l)	200	600	250	1,000	11(56)	6.6 (20)	6.6 (13)	53.3 (80)	53.3 (80)	–	–	Salty taste
SO ₄ ²⁻ (mg/l)	200	400	200	400	–	–	–	20 (46)	20 (46)	–	–	Laxative effect
NO ₃ ⁻ (mg/l)	–	45	45	100	46.6 (60)	40 (60)	60 (74)	73 (80.3)	73 (80.3)	–	–	Methaemoglobinemia
F ⁻ (mg/l)	–	1.5	1.0	1.5	–	–	6.6	–	–	–	–	Fluorosis
Fe (mg/l)	–	0.3	–	1	–	–	–	–	–	–	–	Permotest bactertrial growth
Zn (mg/l)	–	5	5	15	–	–	–	–	–	–	–	Cause astringent taste and an opalescence in water
Mn (mg/l)	–	0.1	0.1	0.3	–	–	–	6.6	6.6	–	–	Adverse affect on domestic uses and water supply structure
Cu (mg/l)	–	1	0.5	1.5	–	–	–	–	–	–	–	Discoloration and corrosion of pipes, fitting and utensils

Values in parenthesis are the percentage of sample having values higher than desirable limit of drinking standard

^a Values are given in comparison to WHO guideline not ISO standard

individual ion concentrations exceed their threshold (WHO 1996a, b). The individual ion concentrations are a function of the geology and other factors such as irrigation. The percentages of samples with conductivity values less than the threshold limit of 1,400 $\mu\text{S}/\text{cm}$ for taste is lowest for post-monsoon period which was 6.6% in Patiala and highest at 40% in Muktsar for pre-monsoon. From Table 6, based on TDS and taste, similar but clearer evidence was noticed. According to which 40% sample of pre-monsoon and 53% of post-monsoon samples of Muktsar fell in unacceptable class of drinking water while none of samples of Patiala fell in this category. An increase in post-monsoon did indicate some leaching of agricultural fertilizer and chemicals with rainwater to the groundwater. It can be concluded that objectionable taste perceptions were highest in areas having higher conductivity values.

Turbidity and colour WHO (1996a, b) suggests that the appearance of water with a turbidity of less than 5 NTU is usually acceptable to consumers, although this may vary

with local circumstances. The consumption of highly turbid water may cause a health risk as excessive turbidity can protect pathogenic micro organisms from the effects of disinfectants, and also stimulate the growth of bacteria during storage. Storage of water is a common practice in rural areas in both the districts. The minimum turbidity at which the colour was unclear (brownish, cloudy or rusty) ranged from 1 to 17 NTU. The fraction of sample with turbidity lower than the minimum detection limit was least for Muktsar (42%) and highest for Patiala (66%). It is possible that the colour in some water samples could have been as a result of rust and other dissolved substances.

Generally, turbidity is dependent on the optical refractive characteristics of colloidal matter. It appears therefore that generally colour objections with a range of 2–12% are not a problem as compared to taste with objectionable taste ranging from 6% in Patiala to 53% in Muktsar districts (Table 7). There was no clear linkage between colour and turbidity.

Table 6 Suitability of groundwater for drinking based on several classification

TDS (mg/l)	Water class	% of Patiala sample		% of Muktsar sample	
		Pre-monsoon	Post-monsoon	Pre-monsoon	Post-monsoon
<300	Excellent	13 (2)	27 (4)	0	0
300–600	Good	40 (6)	20 (3)	47 (7)	7 (1)
600–900	Fair	27 (4)	40 (6)	13 (2)	27 (4)
900–1,200	Poor	20 (3)	13 (2)	0 (0)	13 (2)
>1,200	Unacceptable	0	0	40 (6)	53 (8)
Based on total hardness as CaCO_3 (mg/l) after Sawyer and Mc Cartly (1967)					
<75	Soft	0	0	0	0
75–150	Moderately hard	20 (3)	7 (1)	0	0
150–300	Hard	27 (4)	20 (3)	0	7 (1)
>300	Very hard	53 (8)	73 (11)	100 (15)	93 (14)
Nature of groundwater based on TDS (mg/l) values					
0–1,000	Fresh	87 (13)	100 (15)	60 (9)	27 (4)
1,001–10,000	Brackish	13 (2)	0	40 (6)	73 (11)
10,001–100,000	Salty	0	0	0	0
>100,000	Brine	0	0	0	0

Table 7 Threshold values of water quality parameters for taste and colour as per WHO. The figures in parenthesis are the number of sample with EC or turbidity more than the threshold value. The

threshold value is the minimum value of the parameter at which an objection or complain is raised by the consumer

Parameter	% of Patiala sample		% of Muktsar sample	
	Pre-monsoon	Post-monsoon	Pre-monsoon	Post-monsoon
Objectionable taste ($\mu\text{S}/\text{cm}$)	7 (1)	0	40 (6)	53 (8)
Colour complain (NTU)	7 (1)	7 (1)	14 (2)	14 (2)

Cations, anions and heavy metals contamination

The concentrations of cations, such as Na^+ , Ca^{2+} and Mg^{2+} , were within the maximum permissible limits for drinking, except for a few samples in both the districts. But there is a great difference between the percentage of samples which were between desirable and permissible limits. Those falling beyond permissible limit are alarming and need special attention before the situation becomes worse in near future. In Patiala, not a single sample showed any cation concentration beyond permissible limit. On the other hand, 50 and 70% samples were between desirable and permissible limits of Ca and Mg, respectively. This indicated that groundwater is now getting enriched in these two cations and in the near future, the permissible limit for drinking purposes shall be crossed. In the case of Muktsar, the condition is worse than Patiala. In Muktsar, 20% of pre-monsoon samples were showing concentration beyond permissible limit of magnesium (150 mg/l) and about 73% samples were in between the desirable and permissible limits (DL and PL) thus, almost 93% of samples had Mg concentration more than the desirable limit of drinking water. Some dilution effect was observed in the post-monsoon period and all most all the samples in between DL and PL. In the case of Calcium, scenario is almost same in Muktsar where although only 6.6% samples were beyond permissible limit but 66% samples were in between DL and PL, so only 27.4% of water samples can be said to be good. Potassium is below permissible limit in both the districts because of its low geochemical mobility in fresh water.

Cl^- content is within the permissible limit in Patiala with some exception in pre-monsoon samples, where 6.6% of samples showed higher Cl concentration than permissible limit set by WHO for drinking water, while in Muktsar 53% of samples had more concentration than PL in post-monsoon whereas in pre-monsoon only 6.6% are showing so. This may be due to contribution from anthropogenic and agricultural sources, which leached to groundwater in post-monsoon. Sulphate is unstable if it exceeds the maximum permissible limit of 400 mg/l and causes a laxative effect on humans, together with excess magnesium in groundwater. This may result in gastrointestinal irritation in the human system. As far as nitrate contamination is concerned, both the districts are having this problem only the degree of contamination is different being higher in Muktsar. As there is no natural source of NO_3^- reported in this area, it seems that it is solely contributed by the fertilizer and other anthropogenic activities. In order to investigate fertilizer input as a possible common source of potassium and nitrate to the groundwater, a plot between NO_3^- and K^+ was examined as a higher NO_3^- value should be associated with high K concentration, if source is fer-

tilizer (Datta et al. 1997). The plot indicates that in both districts pre-monsoon season samples show an excess nitrate associated with high potassium content with few exceptions (Fig. 7), but in post-monsoon this relationship did not hold good, perhaps due to dilution effect. This indicates fertilizers as a source of nitrate. Further, high nitrate was associated with low EC. Although the correlation between NO_3^- and K^+ is very weak but at least there is high value of K, associated with high nitrate in pre-monsoon in majority of samples from both districts. It does indicate fertilizer impact but nitrate can have other different sources like animal dung, which is in general practice in Punjab to put it in agriculture field to increase the fertility of soil. North-western and southern parts of Muktsar are the most affected areas from nitrate contamination. Overall, around 40% of Patiala and 60% of Muktsar samples show nitrate concentrations higher than the 45 mg/l permissible limit for drinking water. In comparison to Patiala, higher percentage of samples fall beyond permissible limit for NO_3^- , indicated that Muktsar is more susceptible to this contamination. Even fluoride contamination has been noticed in Muktsar in pre-monsoon samples where as Patiala is free from fluoride contamination. As far as heavy metals are concerned, both districts are almost safe but few samples of Patiala samples of pre-monsoon the areas show Cu contamination while in Muktsar some of the post-monsoon samples are showing Mn contamination also.

Total hardness

Total hardness of the groundwater was calculated using the formula given by (Hem 1985; Ragunath 1987)

$$\text{TH}(\text{as CaCO}_3)\text{mg/l} = (\text{Ca}^{2+} + \text{Mg}^{2+})\text{meq/l} \times 50.$$

The hardness values in Muktsar ranged from 358 to 1,250 mg/l with an average value of 731 mg/l during pre-monsoon and 285.9 to 552.3 mg/l with the average value of 421 mg/l after monsoon. The decrease in the average value of TH after monsoon is due to flushing and dilution. Patiala

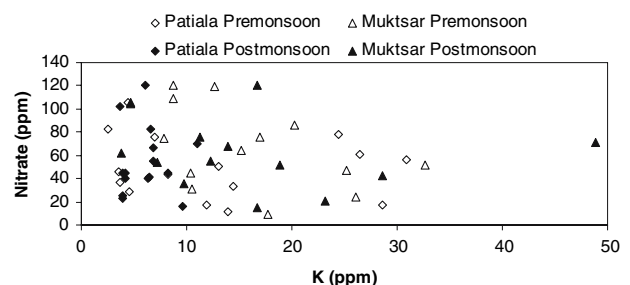


Fig. 7 A cross plot of NO_3^- and K in both districts for two seasons

groundwater is little less in hardness as compared to Muktsar with an average value of 381.7 and 370.7 in the respective seasons. The maximum permissible limit of TH for drinking water is 500 mg/l and the most desirable limit is 100 mg/l as per the WHO international standards. About 86% of pre-monsoon and 20% samples of September 2003 in Muktsar exceeded the maximum permissible limits (Table 5). While in Patiala, the corresponding values are 40 and 13% in the respective seasons. The classification of groundwater (Table 6) based on TH shows that a majority of the samples in both districts is very hard with some exception in Patiala (Sawyer and McCarty 1967).

Thus, apart from nitrate problem, groundwater in Patiala can be deemed fit for drinking purposes but further exploitation may increase fluoride contamination and deteriorate the water quality in near future. While in Muktsar, the condition is really bad which not only is reflected by various contaminations but also by the taste.

Groundwater quality analysis for irrigation

Water quality, soil types and cropping practices play an important role for a suitable irrigation practice. The important chemical constituents that affect the suitability of water for irrigation are the total concentration of dissolved salts, relative proportion of bicarbonate to calcium, magnesium and relative proportion of sodium to calcium. Water quality problems in irrigation include salinity and alkalinity.

Total dissolved solids and EC

To ascertain the suitability of groundwater for any purposes, the TDS should be below 500 mg/l (Catroll 1962; Freeze and Cherry 1979). The Patiala groundwater is fresh water except for a few samples of pre-monsoon showing brackish water. While in Muktsar, 40% of pre-monsoon and 73% of post-monsoon samples are brackish in nature indicating high dissolved load in water (Table 6). Based on the EC (Wilcox 1955) none of the samples fall in either doubtful or unsuitable class for irrigation in Patiala while in Muktsar not only 40% of the sample fall in doubtful class in pre-monsoon but also the same percentage of samples fall in unsuitable category in post-monsoon (Table 8). This indicates leaching and dissolution of salts during post-monsoon in Muktsar.

Sodium adsorption ratio (SAR)

Excessive sodium content relative to the calcium and magnesium reduces the soil permeability and thus inhibits the supply of water needed for the crops. The excess sodium or limited calcium and magnesium are evaluated by SAR which is expressed as

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

All the concentrations in these equations are expressed in equivalent per mole. Irrigation waters are classified based on sodium adsorption ratio (WHO 1989). According to the SAR classification, 100% of Patiala water samples in both the seasons fall in excellent category of (S1) which can be used for irrigation on almost all soils. While in Muktsar, only one location falls in unsuitable (S4) class (Table 8). Therefore, none of the samples are of the poor category for irrigation in either of the seasons. A more detailed analysis for the suitability of water for irrigation was made by plotting the data on US Salinity Laboratory diagram (USSL 1954).

USSL diagram

The analytical data plotted on the US salinity diagram (Richards 1954) illustrates that most of the groundwater samples from both the districts fall in the field C3S1, indicating high salinity and low sodium water, which can be used for irrigation for almost all types of soil with little danger of exchangeable sodium (Fig. 8). However, some scholars argue on the relevancy of this diagram now-a-days, but still we have too few plots available to demonstrate irrigation water classification, hence this diagram is in use even in now-a-days after 50 years of its publication along with the Wilcox diagram. Few post-monsoon samples of Muktsar fall in the field of C4S1, indicating very high salinity but low alkalinity hazard (Fig. 9). This water can be suitable for plants having good salt tolerance but restricts its suitability for irrigation, especially in soils with restricted drainage (Karanth 1989; Mohan et al. 2000). Groundwater samples that fall in the low salinity hazard class (C1) can be used for irrigation of most crops and majority of soils. However, some leaching is required, but this occurs under normal irrigation practices except in soils of extremely low permeability. Groundwater samples that fall in medium salinity hazard class (C2) can be used if a moderate amount of leaching occurs. High salinity water (C3, C4, and C5) cannot be used in soils with restricted drainage. Even with adequate drainage, special management for salinity control is required and crops with good salt tolerance should be selected. Such areas need special attention as far as irrigation is concerned.

Percent sodium (% Na)

Sodium content expressed in terms of sodium percentage or soluble sodium percentage defined as

Table 8 Suitability of Groundwater for irrigation based on several classifications

EC (µS/cm)	Water class	% of Patiala sample		% of Muktsar sample	
		Pre-monsoon	Post-monsoon	Pre-monsoon	Post-monsoon
<250	Excellent	0	7 (1)	0	0
250–750	Good	33 (5)	46.5 (7)	33 (5)	7 (1)
750–2,000	Permissible	67 (10)	46.5 (7)	27 (4)	46 (7)
2,000–3,000	Doubtful	0	0	40 (6)	7 (1)
>3,000	Unsuitable	0	0	0	40 (6)
Based on alkalinity hazard (SAR) after Richards (1954)					
<10	Excellent	S1	100 (15)	100 (15)	93 (14)
10–18	Good	S2	0.0	0.0	0.0
18–26	Doubtful	S3	0.0	0.0	0.0
>26	Unsuitable	S4	0.0	0.0	7 (1)
Based on percent Sodium after Wilcox (1955)					
<20	Excellent	40 (6)	53 (8)	20 (3)	7 (1)
20–40	Good	33 (5)	47 (7)	67 (10)	60 (9)
40–60	Permissible	27 (4)	0	6.5 (1)	26 (4)
60–80	Doubtful	0	0	0	0
>80	Unsafe	0	0	6.5 (1)	7 (1)
% Na (Eaton 1950)					
>60	Safe	100 (15)	100 (15)	93 (14)	93 (14)
<60	Unsafe	0	0	7 (1)	7 (1)
Based on RSC after Richards (1954)					
<1.25	Good	60 (9)	87 (13)	93 (14)	73 (11)
1.25–2.50	Doubtful	13 (2)	0	0.0	7 (1)
>2.50	Unsuitable	27 (4)	13 (2)	7 (1)	20 (3)
Based on residual Mg/Ca ratio					
<1.5	Safe	60 (9)	60 (9)	26.5 (4)	60 (9)
1.5–3	Moderate	33 (5)	27 (4)	47 (7)	20 (3)
>3	Unsafe	7 (1)	13 (2)	26.5 (4)	20 (3)

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

where, all ionic concentrations are expressed in meq/l.

Not a single sample of Patiala groundwater is in doubtful or unsuitable category in any season while in Muktsar only one location behaves differently and falls in unsafe water class in both the seasons in both the classifications given by Eaton (1950) and Wilcox (1955) (Table 8). Using both classifications may help to understand the evolution of different criteria to classify the quality of different types of irrigation water.

The Na % indicates that the groundwater is excellent to permissible for irrigation except one sample of Muktsar. Wilcox (1955) used % sodium and specific conductance in evaluating irrigation waters using the Wilcox diagram as given in Fig. 10. Most of the Patiala water samples in both seasons fall in excellent to good and good to permissible

categories indicating their suitability for irrigation. No water sample is strictly unsuitable for irrigation. While in Muktsar 40% of post-monsoon sample fall in the unsuitable zone while in pre-monsoon, a number of samples fall in doubtful to unsuitable zone for irrigation. When the concentration of sodium is high in irrigation water, sodium ions tend to be absorbed by clay particles, displacing Mg²⁺ and Ca²⁺ ions. This exchange process of Na⁺ in water for Ca²⁺ and Mg²⁺ in soil reduces the permeability and eventually results in soil with poor internal drainage. Hence, air and water circulation is restricted during wet conditions and such soils become usually hard when dry (Saleh et al. 1999).

Residual sodium carbonate

In addition to the SAR and % Na, the excess sum of carbonate and bicarbonate in groundwater over the sum of

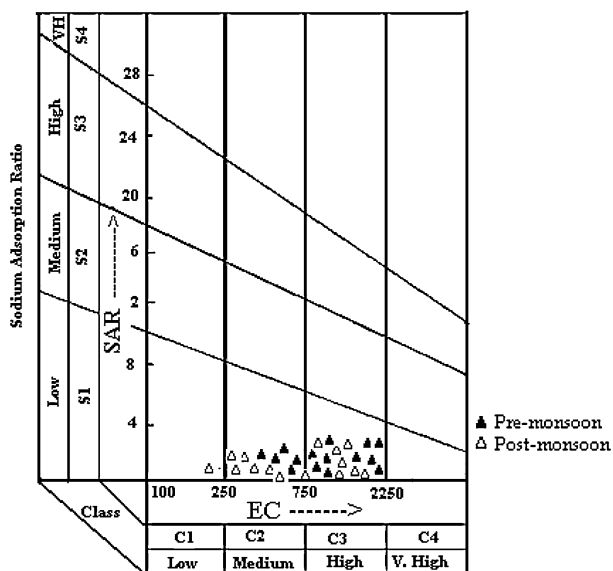


Fig. 8 US salinity diagram for Patiala for pre-monsoon and post-monsoon

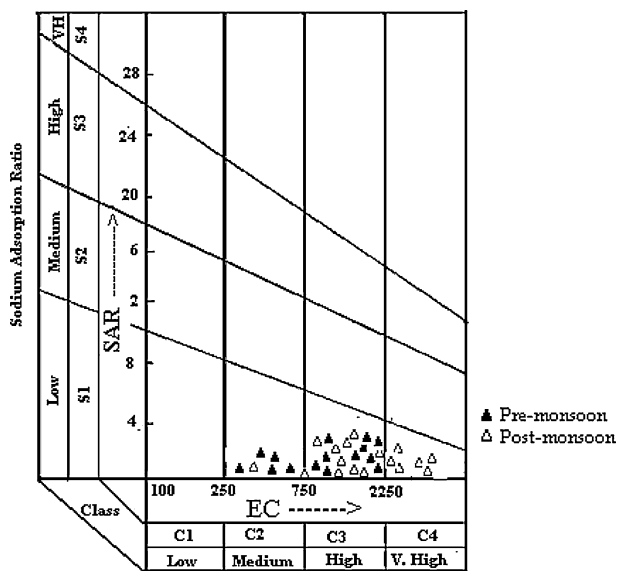


Fig. 9 US salinity diagram for Muktsar for pre-monsoon and post-monsoon

calcium and magnesium also influences the suitability of groundwater for irrigation. An excess quantity of sodium bicarbonate and carbonate is considered to be detrimental to the physical properties of soils as it causes dissolution of organic matter in the soil, which in turn leaves a black stain on the soil surface on drying. This excess is denoted by Residual Sodium Carbonate (RSC) and is calculated as follows (Ragunath 1987):

$$\text{RSC} = (\text{CO}_3^{2-} + \text{HCO}_3^-) - (\text{Ca}^{2+} + \text{Mg}^{2+})$$

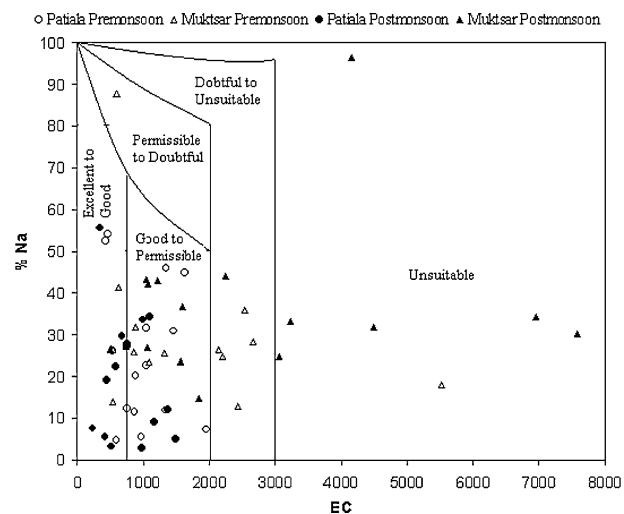


Fig. 10 Suitability of groundwater for irrigation in the Wilcox diagram

where, all ionic concentrations are expressed in meq/l.

The classification of irrigation water according to the RSC values is presented in Table 8, showing rating of waters based on residual sodium carbonate. In Muktsar, the category of pre-monsoon groundwater samples is good with one exception that falls in unsuitable class. The water quality declines in the post-monsoon season and the number of samples in unsuitable category is about 20%. Poor agricultural returns in this area are partly due to this reason. In Patiala, the condition is different as in post-monsoon the quality improves due to recharge of groundwater with rain water. In pre-monsoon 27% of samples fall in unsuitable category which decreases to 13% in post-monsoon. The RSC (expressed in meq/l) varied from -9.05 to 5.76 with an average of -1.15 in pre-monsoon while it varied from -7.94 to 6.98 with an average of -2 in post-monsoon waters of Patiala (Table 1) while the corresponding values for Muktsar are -16.93 to 4.43 and -6.33 in pre-monsoon and -4.99 to 6.05 and -0.14 in post-monsoon periods, respectively (Table 2).

Permeability index

The soil permeability is affected by long-term irrigation influenced by Na^+ , Ca^{2+} , Mg^{2+} and HCO_3^- contents of the soil. The permeability index (PI) values also indicate the suitability of groundwater for irrigation. It is defined as (Ragunath 1987)

$$\text{PI} = \frac{(\text{Na}^+ + \sqrt{\text{HCO}_3^-}) \times 100}{(\text{Ca}^{2+} + \text{Mg}^{2+} + \text{Na}^+ + \text{K}^+)}$$

The concentrations are expressed in meq/l.

The PI ranged from 20.9 to 89.5% during March 2003 with the average value of 41.25% and the corresponding values during September 2003 ranged from 40.35 to 97.9% in Muktsar. The average value was about 52% during post-monsoon, which comes under class-1 of Doneen’s chart (Domenico and Schwartz 1990). In Patiala, higher average value of PI was observed in pre-monsoon than Muktsar while in post-monsoon average PI value is higher in Muktsar than Patiala. Perhaps, this is the reason why different effects of monsoon were observed in both districts. WHO (1989) uses a criterion for assessing the suitability of water for irrigation based on the permeability index. According to the permeability index values, majority of the sample fall under class II category (PI ranged from 25 to 75%) in both the districts, and a slight increase was observed for post-monsoon. In Patiala, 67% of samples fall in class II and increased to 87%, while in Muktsar 87% of pre-monsoon samples increased to 93% in post-monsoon representing class II category.

Index of base exchange

It is essential to know the changes in chemical composition of groundwater during its travel in the sub-surface (Sastri 1994). The Chloro-alkaline indices CAI 1 and CAI 2 are suggested by Schoeller (1977), which indicate ion exchange between the groundwater and its host environment. The Chloro-alkaline indices used in the evaluation of Base Exchange are calculated using the formulae

$$\begin{aligned} \text{Chloro alkaline index 1} &= (\text{Cl} - (\text{Na} + \text{K}))/\text{Cl} \\ \text{Chloro alkaline index 2} &= (\text{Cl} - (\text{Na} + \text{K})/ \\ &\quad (\text{SO}_4 + \text{HCO}_3 + \text{CO}_3 + \text{NO}_3) \end{aligned}$$

If there is ion exchange of Na⁺ and K⁺ from water with magnesium and calcium in the rock, then the exchange is known as direct when the indices are positive. If the exchange is in the reverse order then the exchange is indirect and the indices are found to be negative. The chloro-alkaline indices are calculated for the post-monsoon and pre-monsoon waters of the areas (Tables 1 and 2). It has been observed that 27% of the pre-monsoon and 54% of the post-monsoon samples of Patiala show negative ratios and in Muktsar only 20% for both the seasons. An increase in indirect exchange was observed after monsoon in Patiala but no such effect was observed in Muktsar.

Kelley’s ratio

Sodium measured against Ca²⁺ and Mg²⁺ is used to calculate Kelley’s ratio Kelley (1951). However, now-a-days

SAR is better measure for sodium and this particular ration is not in common use, but this study also presents a review of the all the quality criteria of classification to evaluate the obtained dataset. It varied from 0.03 to 1.06 in the pre-monsoon samples while it ranged from 0.02 to 1.22 in the post-monsoon samples of Patiala with the average value of 0.37 and 0.28, respectively. Therefore, according to Kelley’s ratio, 68% of the samples in the post-monsoon period are suitable for irrigation and 64% for the pre-monsoon. For Muktsar higher Kelley’s ratios were observed. These ranged from 0.13 to 7.14 and 0.1 to 26.83 in pre- and post-monsoon periods, respectively, with an average value nearly ten times higher than Patiala in post-monsoon and two times higher in pre-monsoon. Thus, only 58% of pre-monsoon and 44% of post-monsoon samples are suitable for irrigation in Muktsar.

Magnesium ratios

Generally, calcium and magnesium maintain a state of equilibrium in most waters. More Mg²⁺ present in water will adversely affect the soil quality rendering it alkaline resulting in decreased crop yields. In Patiala, 80% of pre-monsoon samples contained magnesium ratio greater than 50% which was increased to 53% in post-monsoon while in Muktsar, 87% of pre-monsoon and 93% of post-monsoon samples contained magnesium ratio greater than 50%. Thus, Mg is being added up in Muktsar during monsoon while more Ca is being added than Mg in Patiala:

$$\text{Magnesium ratio} = \frac{(\text{Mg}^{2+}) \times 100}{(\text{Ca}^{2+} + \text{Mg}^{2+})}$$

Calcium and magnesium do not behave equally in the soil system and magnesium deteriorates soil structure particularly when waters are sodium dominated and highly saline. High level of Mg is usually due to the presence of exchangeable Na in irrigated soils. Based on the Mg/Ca ratio (Table 8), we can classify waters as suitable or unsuitable for irrigation. In Patiala only seven and 13% of pre- and post-monsoon sample fall in unsuitable category while in Muktsar 20 and 26.5% are unsuitable in the same seasons.

Finally, Table 9 has been prepared on the basis of guideline given for the irrigation water with its potential damage in wastewater engineering book of MetCalf and Eddy (2003), which is adapted from Ayers and Westcot (1985) and Pettygrove and Asano (1985). This table shows the percentage of groundwater with its potential threat on the basis of the irrigation method viz. surface irrigation or sprinkler irrigation. Table 9 clearly shows that sprinkle irrigation method is much more suitable than that of field irrigation.

Table 9 Evaluation for the suitability of groundwater for irrigation based on the Guideline

Potential irrigation problem	Degree of restriction on use			Degree of problem											
				Patiala						Muktsar					
	None (N)	Slight to moderate (S–M)	Severe (S)	Pre-monsoon ^a			Post-monsoon ^a			Pre-monsoon ^a			Post-monsoon ^a		
				N	S–M	S	N	S–M	S	N	S–M	S	N	S–M	S
Salinity (affects crop water availability)															
EC ($\mu\text{S}/\text{cm}$)	<700	700–3,000	>3,000	32	68	–	54	46	–	29	71	–	6	54	40
TDS (mg/l)	<450	450–2,000	>2,000	39	61	–	45	55	–	37	67	–	5	57	38
Permeability (affects infiltration rate of water into the soil) ^b															
SAR = 0–3	EC > 700	700–200	<200	73	27	–	53	40	–	66	27	–	7	86	–
3–6	>1,200	1,200–300	<300	–	–	–	–	–	7	–	–	–	–	–	–
6–12	>1,900	1,900–500	<500	–	–	–	–	–	–	–	–	–	–	–	–
12–20	>2,900	2,900–1,300	<1,300	–	–	–	–	–	–	–	–	7	–	–	7
Specific Ion toxicity (affects sensitive crop)															
(Sodium) Na ⁺															
Surface Irrigation	SAR < 3	3–9	>9	100	–	–	93	7	–	93	–	7	93	–	7
Sprinkler irrigation (mg/l)	<70	>70	–	73	27	–	86	14	–	27	73	–	27	73	–
Cl [–] (mg/l)															
Surface Irrigation	<140	140–350	>350	73	20	7	60	20	20	60	13	37	13	27	60
Sprinkler irrigation	<100	>100	–	53	47	–	60	40	–	40	60	–	7	93	–
Miscellaneous effects (affects susceptible crops)															
Overhead Sprinkling only															
HCO ₃ [–] (mg/l)	<90	90–500	>500	–	87	13	–	87	13	–	60	40	–	67	33

Adopted from Ayers and Westcot (1985), Pettygrove and Asano (1985) and Metcalf and Eddy (2003)

^a Figures are in percentage of sample in the particular categories of degree of problem

^b Evaluated using EC and SAR of the groundwater

Conclusions and recommendations

The hydro-chemical analyses reveal that the present status of groundwater in Patiala is better for irrigation and drinking purposes except for a few locations but it may deteriorate in future, as is evident from the very high percentage of water samples falling beyond the desirable limits according to WHO standards and almost approach the maximum permissible limit. While in the case of Muktsar, it is unsuitable for drinking in the entire district. High TH and TDS at a number of subareas clearly indicate the unsuitability of groundwater for drinking and irrigation purposes. For such areas, adequate drainage and the introduction of alternative salt tolerant crops are required. Such waters can be used either after soil treatment or flushing the soil with excessive of irrigation water. The later alternative is not viable considering the already depleting groundwater reserves, but canal irrigation could be a solution. In terms of monsoon impact, Patiala groundwater shows dilution and flushing by the monsoon

but samples from Muktsar show severe leaching of different chemical constituents to the groundwater leading to enrichment of different anion and cations which eventually indicates pollution from extraneous sources.

It is recommended that this inevitable catastrophic syndrome should be avoided by developing a strategy for water management. This implies conservation and channelling of water from areas where it is plentiful to deficient and scarce areas. Improved farmer economy coupled with various subsidy provided by both the central and state government in the region has resulted in enormous increase in groundwater extraction and fertilizer application which is disturbing the natural water balance. Even irrigation techniques are not efficient. Hence, a time has come to change the present concept of “water supply management” to “water demand management”. An efficient management of water resources should be the main thrust for economic development and improved groundwater quality in India rather than providing different subsidies.

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