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Appraisal of Groundwater Quality of Punjab, India for Irrigation

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Abstract

Study on survey, characterization and classification of groundwater quality in the different districts of Punjab was undertaken with a total of 3525 samples from 22 districts. Out of this, 3267 ground water samples from 8 districts of south-west Punjab were collected by AICRP on Management of Saline Water and Associated Salinization in Agriculture (MSW&ASA), Bathinda, while data of remaining 258 ground water samples from 14 districts were acquired from Central Ground Water Board (CGWB), New Delhi. The ground water samples were analyzed in the laboratory for electrical conductivity (EC), pH, concentrations of cation (Na^+, Ca^{2+} + Mg^{2+}) and anions (CO_3^{2-}, HCO^{3-} and Cl^-). The water samples were categorized into different irrigation water classes as per criterion provided by ICAR-Central Soil Salinity Research Institute, Karnal based on EC, Sodium Adsorption Ratio (SAR) and Residual Sodium Carbonate (RSC). The irrigation water classes include good quality, three subclasses for saline water and three subclasses for alkali water. The data indicated that sub-mountain undulating region (agro climatic region-I) contain the maximum (97.4%) good quality ground water followed by 66.7 % in undulating plain region (agro climatic region-II). However, minimum (20.6%) good quality water samples were recorded from central plain region (agro climatic region-III) followed by 23.6% in western region (agro climatic region-V). It was also reported that 27.9% samples were found in good quality water class "A", 13.7% in marginally saline (B1), 4.7% in saline (B2) and 4.7% in high SAR saline water class (B3), respectively. Among alkali water samples, 8.3% come under marginally alkali (C1), 6.4% in alkali water (C2) and 34.3% in high alkali water class (C3), respectively. In case of anions, HCO_3^- was dominant ion followed by Cl^- and CO_3^{2-} in water samples. These results highlight an increasing issue of declining groundwater quality, which poses threats to crop productivity, soil health, and long-term agricultural sustainability, especially in Punjab central and southwestern districts. In order to ensure sustainable agricultural production and stop further land degradation in Punjab, this study also emphasizes the urgent need for comprehensive water resource management policies.

Keywords: Groundwater quality, Water quality parameter, Saline water, Alkali water, Irrigation water classes

Introduction

The state Punjab extends from the latitudes 29.30° N to 32.32° N and longitudes 73.55° E to 76.50° E covering a total land area of 50362 km^2. The states of Haryana and Rajasthan border it to the south and southwest, Jammu and Kashmir to the north, and Himachal Pradesh to the northeast. The state has a flat alluvial plain except for a narrow belt in the south-western part, where stable sand dunes dot the landscape. The area occupied by the mountains (Himalayan foothills) in northeast, is about 1243 km^2. The state is irrigated by the perennial rivers Sutlej, Beas, Ravi, and the ephemeral river Ghaggar drain. The well establishment of canals caused the state's fertile land to begin turning into green fields and saw remarkable agricultural production success with a focus on growing paddy and high-yielding crops. As a result, the demand for water increased significantly, leading to overuse of groundwater resources. The state has been divided into 22 districts, which are further divided into 77 subdivisions/tehsils and 146 community development blocks. The soils of Punjab largely developed from Indo-Gangetic alluvium, and they primarily fall into four (Inceptisols, Entisols, Aridisols and Alfisols) distinct orders (Sehgal, 2015). Climate, geography, and time all had a

major influence. Punjab's climate is semi-arid throughout the rest of the state, arid in the south and southwest, and semi-humid to semi-arid in the north. There are significant temporal changes because the four wet months of June through September receive more than 75% of the yearly rainfall, which varies greatly in both space and time. Punjab receives an average of 648 mm of rain, although there are significant regional variations.

The main factors influencing the quality of irrigation water are the total soluble salt concentration, the concentration of sodium and its ratio to calcium and magnesium, the concentration of bicarbonates, and the presence of minor elements in excess of allowable levels (Mishra and Banger, 2015). Studies of ground water quality are necessary because its poor quality might have a negative impact on its agricultural users (Chopra and Krishan, 2014; Yadav and Kumar, 2021). Twenty-seven percent of Punjab's land is watered by canals, while the remaining 73% is irrigated by tube wells (Kumar *et al.,* 2008). Crop production and productivity suffer when low-quality ground water is used for crop irrigation. Crop yield losses can be somewhat reduced by following the criteria for irrigating low-quality groundwater. Adoption of guidelines can only be beneficial if planners and farmers have access to geographical data on groundwater quality. To maintain crop production in modern intensive agriculture, it is critical to create a database of groundwater quality characteristics to be utilised for irrigation in a particular area. With this background, groundwater quality survey and characterisation were undertaken for the whole state of Punjab by AICRP on "Management of Saline Water and Associated Salinisation in Agriculture", Bathinda.

Materials and Methods

Study area

Punjab is located in the "Trans-Gangetic Plains Region" or Agro Climatic Zone-VI. The majority of Punjab is located in the fertile plain; the southeast is semi-arid and desert; and the northeast is a band of undulating hills at the base of the Himalayas.

The Ravi, Beas, Sutlej, and Ghaggar are four rivers that flow southwest throughout the state. Punjab is also irrigated by a vast network of canals and divided into six agro climatic regions (Table 1).

Survey and analysis of groundwater quality

The survey was conducted by Regional Research Station, Punjab Agricultural University, Bathinda under the Scheme "All India Coordinated Research Project on Management of Saline Water and Associated salinization in Agriculture" and collected 3267 ground water samples of the 8 districts of south-west, Punjab for determination of groundwater quality during 2015-2022 along

Table 1. Agro-climatic regions of Punjab, India

Zone	Name of zone	Cropping intensity	Average annual rainfall (mm)	Per cent rainfall in monsoon	District covered
1	Sub-Mountain Undulating Region	177	1000-1020	71	Gurdaspur, Hoshiarpur and Pathankot
2	Undulating Plain Region	187	800-9000	77	SAS-Nagar, SBS-Nagar and Rupnagar
3	Central Plain Region	189	500-800	78	Amritsar, Tarn Taran, Kapurthala, Jalandhar, Ludhiana, Fatehgarh Sahib, Sangrur and Patiala
4	Western Plain Region	190	425-700	75	Fazilka, Ferozepur and Faridkot
5	Western Region	193	317-700	78	Muktsar, Bathinda, Barnala, Moga and Mansa
6	Flood Plain Region	-	-	-	Patiala, Ropar, Sangrur, Bathinda and Ferozepur

with GPS locations before monsoon (Table 2). All these samples from 8 districts were collected from running tube wells used for irrigation purposes. The water samples were analyzed for various chemical properties like pH, electrical conductivity (EC), CO_3^{2-}, HCO_3^-, Cl^-, Na^+, Ca^{2+} + Mg^{2+}, by the procedure outlined in USDA Handbook No. 60 (Richards, 1954). Sodium adsorption ratio (SAR) and residual sodium carbonate (RSC) in water samples were calculated using following equations where all values of cations and anions are in me L^{-1}.

$$SAR(\text{m mol } L^{-1})^{1/2} = \frac{Na^+}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}}$$

$$RSC\ (\text{me } L^{-1}) = (CO_3^{2-} + HCO^{3-}) - (Ca^{2+} + Mg^{2+})$$

The data related to ground water quality along with their GPS locations of remaining 14 districts (Table 2) were procured from the reports (2018-2022) of Central Ground Water Board (CGWB) New Delhi. Details of the collected data are provided in Table 2. The irrigation water quality category of each sample was classified on the basis of criteria given by Central Soil Salinity Research Institute (CSSRI), Karnal, Haryana presented in Table 3 (Gupta *et al.,* 1994; Minhas *et al.*, 1998). Total 3225 number of ground water samples from whole Punjab were used for categorization of irrigation water quality.

Results and Discussion

Ground water quality in Punjab

The suitability of groundwater quality for the intended irrigation application depends on several parameters. It assists not only in determining the appropriateness but also in implementing practical corrective actions to enhance according to scientific principles. Groundwater is a significant irrigation resource in most rural areas, particularly where surface water is insufficient or nonexistent. Table 4 shows the range of concentrations of different cations and anions in groundwater in each district. The same data was used to determine the SAR and RSC. Table 4 shows the ranges for various ground water quality metrics per district.

Description of groundwater quality in different agro-climatic regions

The quality of groundwater samples of sub-mountain undulating regions indicated that pH, EC, SAR and RSC ranged from 7.12-8.86, 0.19-2.13 dS m^{-1}, 0.12-5.43 (mmol $L^{-1})^{1/2}$ and 0-2.85 me L^{-1}, with highest mean value of pH (8.41) in Pathankot, EC (0.71 dS m^{-1}), RSC (0.36 me L^{-1}) and SAR (1.69 mmol $L^{-1})^{1/2}$ in Gurdaspur (Table

Table 2. Ground water samples collected/ procured from different districts of Punjab by AICRP-MSW&ASA, Bathinda and CGWB, New Delhi

AICRP, Bathinda				CGWB, New Delhi			
S. No.	District	Area	No of samples	S. No.	District	Area	No of samples
1	Barnala	1410	278	1	Amritsar	2647	16
2	Bathinda	3385	344	2	Fatehgarh Sahib	1180	12
3	Faridkot	1469	541	3	Gurdaspur	2635	31
4	Fazilka	3113	583	4	Hoshiarpur	3365	30
5	Firozpur	2190	466	5	Jalandhar	2632	19
6	Mansa	2171	411	6	Kapurthala	1632	9
7	Sangrur	3610	332	7	Ludhiana	3767	26
8	Sri Muktsar Sahib	2615	312	8	Moga	2216	9
				9	SAS Nagar	1093	19
				10	Pathankot	929	16
				11	Patiala	3218	30
				12	Rupnagar	1369	15
				13	SBS Nagar	1267	8
				14	Tarn Taran	2449	18
	Total Samples		3267		Total Samples		258

Table 3. Groundwater categorization for irrigation purpose

Water quality	EC (dS m^{-1})	SAR (mmol $L^{-1})^{1/2}$	RSC (me L^{-1})
A.Good	< 2	< 10	< 2.5
B. Saline			
B1-Marginally Saline	2- 4	< 10	< 2.5
B2- Saline	> 4	< 10	< 2.5
B3- High –SAR Saline	> 4	> 10	< 2.5
C. Alkaline Water			
C1- Marginally alkaline	< 4	< 10	2.5-4.0
C2- Alkaline	< 4	< 10	> 4.0
C3- Highly alkaline	Variable	> 10	> 4.0

4). Among the cations Ca^{2+}+Mg^{2+} ranged from 0.45-5.65 me L^{-1} with highest value in district Pathankot followed by Gurdaspur and Hoshiarpur. Among the anions HCO_3^- was the dominant one and ranged from 76-531 me L^{-1} followed by Cl^- (4-256 me L^{-1}) and CO_3^{2-} (0.0-46 me L^{-1}). Only 2.6% samples in the region showed EC value greater than 2.0 dS m^{-1}, and those samples belonged to the marginally saline category (B1).

The pH, EC, SAR and RSC of undulating plain region samples ranged from 7.76-9.19, 0.35-1.57 dS m^{-1}, 0.34-10.65 (mmol $L^{-1})^{1/2}$ and 0-9.54 me L^{-1}, with highest mean value of pH (8.41) in SAS Nagar, EC (0.77 dS m^{-1}) and SAR (2.04 mmol L^{-1}) in Rupnagar, RSC (0.12 me L^{-1}) in SBS Nagar (Table 4). Among the anions, HCO_3^- was the dominant one and ranged from 71-569 me L^{-1} with highest mean value of 263.9 me L^{-1} in Rupnagar followed by Cl^- (7-1546 me L^{-1}) and CO_3^{2-} (0.0-154 me L^{-1}). The cations Ca^{2+} + Mg^{2+} in the water ranged from 1.13-18.76 me L^{-1} with the highest value in district SAS Nagar, followed by Rupnagar and SBS Nagar. 2.4% samples in the region showed EC value greater than 4.0 dS m^{-1}, belonged to High-SAR saline category (B3). However, 19% and 12 % samples were categorized as marginal alkaline (C1) and highly alkaline (C3), respectively.

The quality of groundwater samples from districts of central plain regions indicated that pH, EC, SAR and RSC ranged from 7.85-9.31, 0.22-3.45 dS m^{-1}, 0.34-33.76 (mmol $L^{-1})^{1/2}$ and 0-14.2 me L^{-1}, with highest mean value of pH (8.77) and EC (1.05 dS m^{-1}) in Sangrur followed by Patiala (8.72) and (0.99 dS m^{-1}).The highest mean RSC (4.11 me L^{-1}) was recorded in Tarn Taran followed by Sangrur (3.53 me L^{-1}) and highest mean SAR (6.87 mmol L^{-1}) was observed in Sangrur followed by Tarn Taran (5.86 mmol L^{-1}). The HCO_3^- was the dominant anions and ranged from 45-674 me L^{-1} with higher mean value 382.1 me L^{-1} in Tarn Taran followed by 325.8 me L^{-1} in Amritsar and 303.81 me L^{-1} in Sangrur (Table 4). The Cl^- ranged from 7-567 me L^{-1} with higher mean value 80.50 me L^{-1} in Sangrur followed by 77.9 me L^{-1} in Patiala and 73.5 me L^{-1} in Ludhiana. The CO_3^- content in water varied from 0-219 me L^{-1} with higher mean value 51.70 me L^{-1} in Sangrur followed by 39.4 me L^{-1} in Tarn Taran and 33.6 me L^{-1} in Patiala. The cation (Ca^{2+} + Mg^{2+}) content in water ranged from 0.19-9.88 me L^{-1} with highest mean value 2.48 me L^{-1} in Ludhiana followed by 2.12 me L^{-1} in Amritsar and 1.94 me L^{-1} in Fatehgarh Sahib. Most of the ground samples (74%) of this region belong to the highly alkali water (C3) category.

The western plain regions groundwater samples quality (Table 4) indicated that pH, EC, SAR and RSC ranged from 6.4-10.1, 0.10-9.50 dSm^{-1}, 0-143.5 (mmol $L^{-1})^{1/2}$ and 0-50 me L^{-1}, with highest mean value of pH (8.61) and SAR (53.74 mmol L^{-1}) in Firozpur, EC (2.47 dS m^{-1}) in Faridkot, RSC (8.66 me L^{-1}) in Fazilka. Among the cations, Ca^{2+} + Mg^{2+} ranged from 0.55-61.0 me L^{-1} with highest value in district Fazilka (7.25 me L^{-1}) followed by Faridkot (4.21 me L^{-1}) and Firozpur (3.39 me L^{-1}). Among the anions, HCO_3^- was the dominant one and ranged from 1-813 me L^{-1} followed by Cl^- (1-1779 me L^{-1}) and CO_3^- (0.0-187 me L^{-1}). Only 2.6% of samples in the region showed EC value greater than 2.0 dS m^{-1} and those samples belonged to marginally saline category (B1). The ground water of this region belongs to each category viz. good quality (29%), Saline water (31%) and alkali water (40%).

The western regions ground water pH, EC, SAR and RSC ranged from 7.65-9.54, 0.24-5.53 dS m^{-1}, 0.12-24.98 (mmol $L^{-1})^{1/2}$ and 0-22.21 me L^{-1}, with highest mean value of pH (9.07) and SAR (8.81 mmol L^{-1}) in Mansa, EC (2.52 dS m^{-1}) in Sri Muktsar Sahib, RSC (2.92 me $L^{-1)}$ in Barnala (Table 4). Among the anions HCO_3^- was the dominant one and ranged from 97-1356 me L^{-1}

Table 4. Range and average of various parameters of ground water quality in different districts of Punjab

District	Samples	pH	EC dS m^{-1}	CO_3^{2-}	HCO_3^-	Cl^- me L^{-1}	$Ca^{2+}+ Mg^{2+}$	RSC	SAR $(mmol\ L^{-1})^{1/2}$
Sub-mountain undulating region									
Gurdaspur	31	7.74-8.82	0.22-1.99	0-45	117-531	7-256	0.88-4.7	0-2.85	0.25-5.43
		(7.98)	(0.71)	(12.50)	(270.6)	(34.6)	(2.31)	(0.36)	(1.69)
Hoshiarpur	30	7.12-8.76	0.22-1.04	0-46	87-343	4-117	0.45-3.9	0-1.85	0.43-3.15
		(7.82)	(0.45)	(3.28)	(195.5)	(30.5)	(1.81)	(0.21)	(0.96)
Pathankot	16	7.76-8.86	0.19-2.13	0-45	76-287	4-205	0.48-5.65	0-1.23	0.12-4.23
		(8.41)	(0.58)	(15.90)	(197.4)	(49.3)	(1.82)	(0.14)	(0.99)
Undulating plain region									
SBS- Nagar	8	8.31-8.55	0.36-0.83	0-31	121-243	15-165	1.14-2.67	0-1.98	0.34-2.87
		(8.11)	(0.64)	(14.35)	(135.5)	(65.5)	(1.42)	(0.12)	(1.67)
SAS- Nagar	19	7.76-9.19	0.62-9.01	0-154	72-569	14-1546	1.21-18.76	0-9.54	1.61-10.65
		(8.41)	(0.54)	(20.81)	(173.4)	(48.4)	(1.84)	(0.11)	(1.53)
Rupnagar	15	7.84-8.86	0.35-1.57	0-61	71-467	7-174	1.13-5.01	0-3.12	0.35-4.63
		(8.20)	(0.77)	(15.6)	(263.9)	(52.4)	(2.65)	(0.11)	(2.04)
Central plain region									
Amritsar	16	7.85-8.46	0.37-1.38	0-20	210-555	9 -118	0.95-3.60	0-4.15	0.85-4.95
		(8.14)	(0.77)	(5.15)	(325.8)	(54.65)	(2.12)	(1.14)	(2.42)
Fatehgarh Sahib	12	8.35-8.95	0.46-1.56	12-42	123-154	2-278	1.24-5.12	0-3.43	1.35-4.32
		(8.64)	(0.75)	(24.9)	(125.8)	(60.84)	(1.94)	(0.56)	(2.77)
Jalandhar	19	8.11-8.76	0.22-1.12	0-82	107-265	10-121	0.34-2.5	0-3.11	0.34-10.74
		(8.45)	(0.45)	(26.4)	(170.9)	(30.21)	(1.62)	(0.39)	(2.25)
Kapurthala	9	8.11-7.68	0.30-0.81	0-61	106-278	7-125	0.46-3.33	0-3.87	0.71-8.65
		(8.41)	(0.57)	(29.9)	(147.6)	(55.01)	(1.61)	(0.23)	(3.41)
Ludhiana	26	8.21-8.87	0.35-3.45	0-135	45-465	7-567	1.13-9.88	0-5.44	0.34-5.91
		(8.45)	(0.87)	(23.7)	(197.9)	(73.5)	(2.48)	(0.35)	(2.94)
Patiala	30	8.13-9.15	0.33-2.60	0-86	110-432	7-229	0.65-4.76	0-6.34	0.35-13.87
		(8.72)	(0.99)	(33.6)	(245.9)	(77.9)	(1.85)	(1.72)	(5.41)
Sangrur	332	8.39-9.31	0.36-3.04	12-219	176-476	7-319	0.19-4.12	0-10.87	0.65-18.98
		(8.77)	(1.05)	(51.70)	(303.81)	(80.50)	(1.59)	(3.53)	(6.87)
Tarn Taran	18	8.11-9.14	0.43-1.47	0-97	178-674	9-98	0.21-3.43	0-14.2	0.97-33.76
		(8.64)	(0.83)	(39.4)	(382.1)	(41.2)	(1.84)	(4.11)	(5.86)
Western plain region									
Faridkot	541	7.98-9.24	0.45-8.67	0-132	85-576	34-1534	0.85-23.01	0-12.7	2.0-23.85
		(8.58)	(2.47)	(38.2)	(232.32)	(325.65)	(4.21)	(0.21)	(9.73)
Fazilka	583	6.4-10.1	0.10-9.50	0-9.5	1-1.5	1-78	2-61	0-50	0-11
		(7.78)	(2.14)	(2.14)	(0.11)	(6.46)	(7.25)	(8.66)	(1.25)
Firozpur	466	7.76-9.21	0.51-7.58	0-187	134-813	14-1779	0.55-17.3	0-15.4	0.62-143.5
		(8.61)	(2.13)	(46.72)	(320.6)	(232.75)	(3.39)	(0.29)	(53.74)
Western region									
Bathinda	313	7.95- 9.54	0.30-4.95	0-202	97-1356	7-386	0.31-10.1	0-22.21	0.12-24.98
		(8.68)	(1.73)	(42.63)	(445.6)	(145.23)	(3.57)	(1.63)	(6.85)
Barnala	278	8.51-9.18	0.25-1.15	12-72	110-475	14-85	1.35-2.62	0-5.56	0.18-6.65
		(8.79)	(078	(50.3)	(317.2)	(52.4)	(2.02)	(2.92)	(3.88)
Mansa	278	8.65-9.53	0.25-5.24	6-124	97-865	7-676	0.61-6.34	0-16.76	0.14-24.87
		(9.07)	(1.53)	(45.01)	(332.90)	(145.12)	(2.65)	(2.02)	(8.81)
Moga	9	7.65-9.43	0.24-3.68	0-121	157-564	14-453	1.34-9.88	0-10.86	0.29-14.83
		(8.85)	(1.29)	(46.9)	(341.2)	(108.7)	(3.52)	(0.24)	(5.83)
Sri Muktsar	312	8.12-8.87	1.09-5.53	0-76	265-987	56-1232	1.43-12.87	0-3.43	2.28-12.65
Sahib		(8.32)	(2.52)	(28.54)	(421.56)	(371.50)	(5.12)	(0.12)	(6.42)
Flood plain region (districts of different agro climatic regions)									
Bathinda	313	7.95- 9.54	0.30-4.95	0-202	97-1356	7-386	0.31-10.1	0-22.21	0.12-24.98
		(8.68)	(1.73)	(42.63)	(445.6)	(145.23)	(3.57)	(1.63)	(6.85)
Firozpur	466	7.76-9.21	0.51-7.58	0-187	134-813	14-1779	0.55-17.3	0-15.4	0.62-143.5
		(8.61)	(2.13)	(46.72)	(320.6)	(232.75)	(3.39)	(0.29)	(53.74)
Patiala	30	8.13-9.15	0.33-2.60	0-86	110-432	7-229	0.65-4.76	0-6.34	0.35-13.87
		(8.72)	(0.99)	(33.6)	(245.9)	(77.9)	(1.85)	(1.72)	(5.41)
Rupnagar	15	7.84-8.86	0.35-1.57	0-61	71-467	7-174	1.13-5.01	0-3.12	0.35-4.63
		(8.20)	(0.77)	(15.6)	(263.9)	(52.4)	(2.65)	(0.11)	(2.04)
Sangrur	332	8.39-9.31	0.36-3.04	12-219	176-476	7-319	0.19-4.12	0-10.87	0.65-18.98
		(8.77)	(1.05)	(51.70)	(303.81)	(80.50)	(1.59)	(3.53)	(6.87)

*Value in parenthesis is mean of the parameters

with highest mean value of 445.6 me L^{-1} in Bathinda followed by Cl^- (7-1232 me L^{-1}) with highest mean value of 371.5 me L^{-1} in Sri Muktsar Sahib and CO_3^- (0.0-202 me L^{-1}) with highest mean value of 50.3 me L^{-1} in Barnala. The cations Ca^{2+} + Mg^{2+} in the water ranged from 0.31-12.87 me L^{-1} with highest mean value (5.12 me L^{-1}) in district Sri Muktsar Sahib followed by Bathinda (3.57 me L^{-1}) and Moga (3.52 me L^{-1}). In this region 23, 25 and 52% water samples belong to good, saline and alkali category, respectively.

The floodplains regions of Punjab are highly susceptible to flooding, especially during the monsoon season. The samples indicated that pH, EC, SAR and RSC ranged from 7.76-9.54 with highest mean value (8.77) in Sangrur, 0.30-7.58 dS m^{-1} with highest mean value (2.13 dS m^{-1}) in Firozpur, 0.12-143.5 (mmol $L^{-1})^{1/2}$ with highest mean value of 53.74 (mmol $L^{-1})^{1/2}$) in Firozpur and 0-22.21 me L^{-1} with highest mean value (3.53 me L^{-1}) in Sangrur. The HCO_3^- was the dominant anions and ranged from 71-1356 me L^{-1} with highest mean value of 445.6 me L^{-1} in Bathinda followed by 320.6 me L^{-1} in Firozpur and 303.81 me L^{-1} in Sangrur. The Cl^- ranged from 7-1779 me L^{-1} with highest mean value 232.75 me L^{-1} in Firozpur followed by 145.23 me L^{-1} in Bathinda and 80.50 me L^{-1} in Sangrur. The CO_3^- content in water varied from 0-219 me L^{-1} with highest mean value 51.70 me L^{-1} in Sangrur followed by 46.72 me L^{-1} in Firozpur and 42.63 me L^{-1} in Bathinda. The cation (Ca^{2+} + Mg^{2+}) content in water ranged from 0.19-17.3 me L^{-1} with highest mean value 3.57 me L^{-1} in Bathinda followed by 3.39 me L^{-1} in Firozpur and 2.65 me L^{-1} in Rupnagar (Table 4). Like the western region, the water samples of this region also belong to good (24%), saline (18%) and alkali categories (58%).

Kumar *et al*. (2013) and reports of the central ground water board (2022 and 2023) reported the average electrical conductivity was 1.37 dS m^{-1}, with a range of 0.42 to 5.75 dS m^{-1} in the state. Bicarbonate in water varied from 0.08 to 16.39 me L^{-1}, while CO_3^- ranged from 0 to 4.0 me L^{-1}. The range of Cl^{-1} was 0.20 to 66.21 me L^{-1}. The mean value of Ca^{2+} + Mg^{2+} was 5.25 me L^{-1}, with a range of 0.37 to 37.78 me L^{-1}. The range of RSC varied from 0 to 21.30 me L^{-1}, however, average SAR was 2.66 (mmol $L^{-1})^{1/2}$ with a range of 0.0 to 34.78 (mmol $L^{-1})^{1/2}$. Many researchers have reported similar findings on water quality in the southwestern region of Punjab (Sharma *et al.,* 2016; Yadav and Sekhon, 2016; Yadav *et al.,* 2018; Yadav, 2021; Yadav and Kumar, 2021; Yadav and Grover, 2023).

Ground water quality distribution in different agro climatic zones

Out of the six agro climatic zones of Punjab, only zone-I (sub-mountain undulating region) had good quality water in 97.4% samples, followed by zone-II (undulating plain region), which had 66.7 % samples with good quality water (Table 5). On the other hand, zone-III (central plain region) contains minimum (20.6%) good quality water samples followed by zone V/VI (western region/ flood plain region) and zone-IV (western plain region) having about 23.6 % and 23.8% good quality water samples. The zone IV (western plain region) and zone-V (western region) had 30% and 24% saline water samples. However, maximum (80%) water samples under alkali nature were recorded in zone-III (central plain region) followed by zone VI / V (flood plain region /western region) with 58 % and 52% water samples. Whereas none of the samples in alkali water category was recorded in zone-I (sub-mountain undulating region), while, 31% and 40 % samples were recorded as alkali water in zone-II (undulating plain region) and zone-IV (western plain region).

The Central Ground Water Board (2022 & 2023) indicated that ground water in the northern and central regions of Punjab belongs to the C2S1 and C3S1 classes of irrigation water based on EC and SAR. It suggests that the majority of these waters can be used to irrigate crops that can tolerate semi-saline conditions on any type of soil. Groundwater from the southern and southwestern regions, which include the districts of Bhatinda, Faridkot, Fazilka, Ferozepur, Mansa, Muktsar, and Patiala, is primarily classified as C3S2, C3S3, C3S4, C4S1, C4S2, C4S3, and C4S4. Continuous usage of such water for irrigation is likely to result in salinity problems and reduced yields of crops. Similarly, according to groundwater RSC values,

Table 5. Distribution of groundwater quality in different districts of Punjab

District	No. of sample	Categories of Groundwater samples (%)						
			B. Saline water			C. Alkali water		
		A Good water	B1 Marginally saline	B2 Saline	B3 High SAR saline	C1 Marginally alkali	C2 Alkali	C3 High alkali
Sub-mountain undulating region								
Gurdaspur	31	97	3	0	0	0	0	0
Hoshiarpur	30	100	0	0	0	0	0	0
Pathankot	16	94	6	0	0	0	0	0
Undulating plain region								
SAS- Nagar	19	58	0	0	5	21	0	16
SBS- Nagar	8	100	0	0	0	0	0	0
Rupnagar	15	60	0	0	0	27	0	13
Central plain region								
Amritsar	16	81	0	0	0	0	19	0
Fatehgarh Sahib	12	67	0	0	0	0	33	0
Jalandhar	19	79	0	0	0	11	11	0
Kapurthala	9	89	0	0	0	11	0	0
Ludhiana	26	88	0	0	0	12	0	0
Patiala	30	53	3	0	3	0	10	30
Sangrur	332	2	0	0	0	0	0	99
Tarn Taran	18	39	0	0	0	17	33	11
Western plain region								
Faridkot	541	15	27	13	3	15	10	16
Fazilka	583	30	23	4	1	6	8	28
Firozpur	466	44	7	6	6	11	12	15
Western region								
Bathinda	344	14	18	6	15	10	6	33
Barnala	278	71	2	0	0	20	8	0
Mansa	411	16	18	5	7	4	2	48
Moga	9	67	0	0	0	0	22	11
Sri Muktsar Sahib	312	2	7	5	12	1	1	73
Flood plain region (districts of different agro climatic regions)								
Bathinda	344	14	18	6	15	10	6	33
Firozpur	466	44	7	6	6	11	12	15
Patiala	30	53	3	0	3	0	10	30
Rupnagar	15	60	0	0	0	27	0	13
Sangrur	332	2	0	0	0	0	0	99

55.15% of the waters are safe, 11.82% are marginal, and the remaining 33.03% are unsuitable for irrigation. On soils that are well-drained, the majority of groundwater from Amritsar, Fatehgarh Sahib, Gurdaspur, Hoshiarpur, Jallandhar, Kapurthala, Ropar, and Patiala can be used to irrigate crops that can tolerate some salt. The irrigation rating of the waters from the districts of Bathinda, Faridkot, Ferozepur, Mansa, Muktsar, and Sangrur differs greatly (CGWB, 2022 & 2023). The findings of Sharma *et al.* (2016); Yadav and Sekhon (2016); Yadav *et al.,* (2018), Yadav (2021); Yadav and Kumar (2021); Yadav and Grover (2023) are all supported by these results.

Conclusions

The groundwater quality data of Punjab indicated that on the bases of 3530 samples analyzed, 982 samples were found in good water category "A" (27.8%), 484 samples (13.7%) fall in marginally saline (B1), 170 samples (4.8%) in saline (B2) and 168 samples (4.8%) in high SAR saline water category (B3), respectively. Among alkali water

category, 225 samples (8.3%) come under the category of marginally alkali (C1), 225 samples (6.4%) in alkali water (C2) and 1209 samples (34.2%) in high alkali water category (C3), respectively. The sub-mountain undulating region had the good quality water. The central plain region had the good quality water along with C1, C2 and C3 type. The others region of the state had the good quality water along with varying amount of saline (B1, B2 and B3) and alkali (C1, C2 and C3) water. The information on groundwater quality classes and management practices would be useful for better planning of poor-quality groundwater for irrigation purpose in Punjab.

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