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Mapping Ground Water Quality in Sri Muktsar Sahib District, Punjab Using Geo-statistics

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Abstract

Systematic survey was carried out to assess the ground water quality of Muktsar district of Punjab using geo-statistics during post monsoon season (December–February) 2013–14. Geo-referenced ground water samples were collected in regular grid in post monsoon season; and analysed for pH, electrical conductivity (EC), total hardness (Ca^{2+}+Mg^{2+}), sodium (Na^+) and potassium (K^+), carbonate and bi-carbonate (CO_3^{2-}, HCO_3^-), chloride (Cl^-) and sulphate (SO_4^{-2}). Residual Sodium Carbonate (RSC) and Sodium Adsorption Ratio (SAR) were calculated using standard formula. Ground water quality was evaluated on the basis of EC and RSC. Spatial distribution of ground water quality parameters and overall, ground water quality was assessed and mapped though geostatistical approach. The best semi-variogram model for every parameter varied based on the root mean square error (RMSE) criterion. Salinity hazard in ground water was prominent in the eastern and southern part of the district and 41.1% of total geographic area (TGA) of the district was irrigated with highly to extremely saline ground water (EC>4 and >6 dS m^{-1}, respectively and RSC<2.5 me l^{-1}). Non saline non sodic ground water (EC<2 dS m^{-1} and RSC<2.5 me l^{-1}) was available only in 10.6% of TGA whereas, slight to moderate sodic ground water prevailed in a very small area (1.6% of TGA of the district). Mixing of canal water with ground water, selection of appropriate crops, salt tolerant varieties may be alternative measures for rational use of water and preventing further deterioration.

Keywords: Ground water quality, geo-statistics, total geographical area

1. Introduction

Improved irrigation system is one of the major factors contributing to dramatic rise in agricultural production in Punjab in post green revolution era. As per Statistical Abstract of Punjab, 2020, about 99% of the net sown area of the state is irrigated, out of which 27% depends on surface irrigation and rest 73% on ground water through tube wells. There are 12.76 lakhs electric and diesel operated tube wells in Punjab (Anonymous, 2020). So, assessment of ground water quality in regular interval is important to delineate different water management zones for precise and planned application of the water; and maintain sustainability of crop production in a state like Punjab. The groundwater quality depends on lithological, pedogeochemical compositions, human activities and various geochemical compositions of the rocks (Adimalla et al., 2018, Adimalla and Venkatayogi., 2018, Narsimha and Sudarshan, 2013, Li et al., 2017). Industrialization and other anthropogenic activities are sharply deteriorating the quality of ground water (Kaur et al., 2017, Ahada and Suthar, 2018) and resulting into increasing health hazards (Adimalla, 2019). In Punjab, natural drainage from northeast to southwest direction along with dense canal irrigation network and inadequate drainage system have aggravated the problem. Water logging and rise in ground water table at the rate of 15–20 cm annum^{-1} in the affected districts has been reported (Shakya et al., 1995) resulting in elevated salinity and sodicity hazards in ground water. Application of poor quality of water in the field for irrigation is harmful for crop health and may also induce salinity and sodicity hazards in soil in long term. In such a context ground water quality assessment study for irrigation water was attempted for Muktsar district in integrated geographical information system (GIS) using a geostatistical approach (kriging) to accurately model the spatial distribution pattern of irrigation water quality parameters. Application of GIS and geostatistical approach in ground water quality assessment has been reported by various researchers (Gozdowski et al., 2015, Demir et al., 2009, Adhikary et al., 2010). The role of GIS in analyzing the spatial distribution of groundwater quality has been investigated by many authors (Verma et al., 2016, Gorai and Kumar, 2013, Srivastava et al., 2012). Kriging is the most popular one among different interpolation techniques for making optimal, unbiased estimates of regionalized variables at unsampled locations using the structural properties of the semi-variogram and the initial set of data values (Shi, 2014). Irrigation water quality assessments through GIS approach have been attempted by several researchers in India (Adhikari et al., 2012, Krishna et al., 2015, Subramani and Nancy Priya., 2021) and particularly in different districts of Punjab (Sahoo et al., 2014, Kundu and Sood, 2019) also. Therefore, the present study aimed to assess and map the quality of irrigation water in the Muktsar district of Punjab with the help of spatial variability maps of quality determining parameters generated using the interpolation technique in GIS environment.

2. Materials and Methods

2.1. Study area

The survey was carried out at Muktsar district of Punjab using geo-statistics during post monsoon season (December–February) 2013–14. Muktsar district lies in the south western zone of Punjab, which is popularly known as cotton belt, however during the last few years the problems of water logging and salinity in this district are compelling the farmers to bring the waterlogged area under rice. It lies between 74º 15' 03" to 74° 49’ 32” E longitudes and 29° 53' 31" to 30° 40' 43" N latitudes and was carved out from the erstwhile Faridkot district in 1995 covering an area of 2636 km^2 which is 5.23% area of Punjab state. The climate of the district is more or less typical of Punjab plains. It has extremely hot and dry summer season. The normal annual rainfall of Muktsar district is 380 mm in 22 days which is unevenly distributed over the district. The southwest monsoon contributes about 79% of annual rainfall and rest 21% of the annual rainfall occurs during non-monsoon months of the year in the form of thunder storm and western disturbances.

Physio-graphically the area has no river and is covered extensively by the canal network. Seepage from canals and poor drainage because of flat topography of the district has resulted into rise in ground water table, flooding; and salinity and sodicity hazards in ground water.

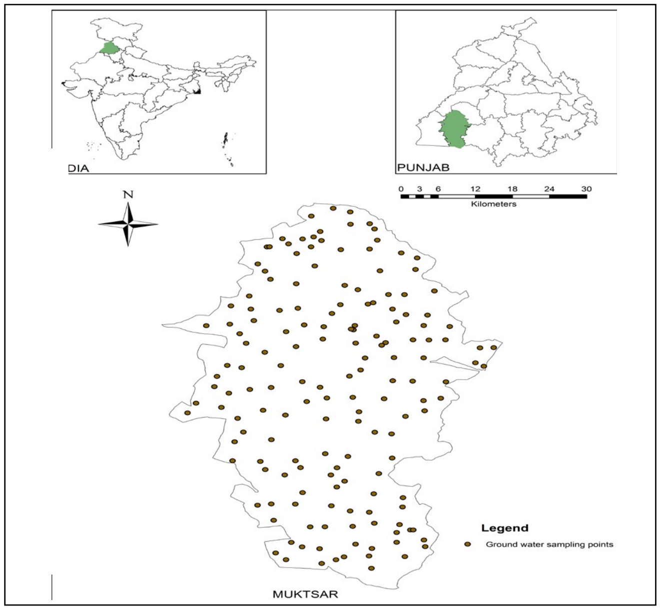
2.2. Ground water sampling and chemical analysis

Ground water samples (georeferenced) from 162 running tube wells were collected in 4 km×4 km regular grid during post monsoon season (December–February, 2013–14). The samples were analysed for pH, electrical conductivity, total hardness (Ca^{2+}+Mg^{2+}), sodium (Na^+), potassium (K^+), total bi-carbonate (CO_3^{2-}+ HCO_3^-), chloride (Cl^-) and sulphate (SO_4^{-2}) quantitatively using standard methods (Anonymous, 1992). Residual Sodium Carbonate (RSC) and SAR were calculated using the formula:

$$\text{RSC (me L}^{-1}\text{)}=(CO_3^{2-}+ HCO_3^-)-(Ca^{2+}+Mg^{2+}) \quad \text{.........................(1)}$$

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

The locations of water sampling sites were marked using Global Positioning System (GPS) (Map 1).



Map 1: Ground water sampling points in Muktsar district

2.3. Categories of ground water samples

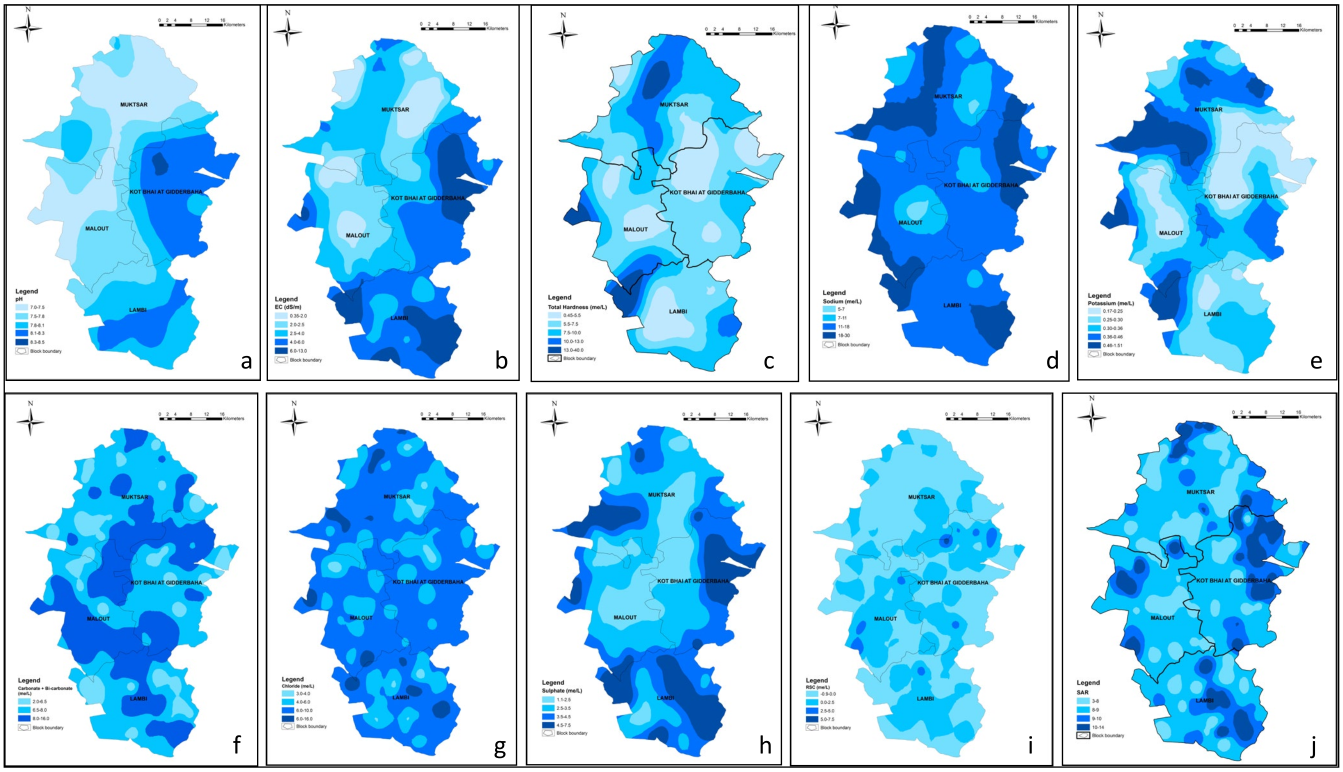
Salinity and sodicity hazards were evaluated by USSL (Richards, 1954) and EEC classification (Lloyd and Heathcote, 1985), respectively (Table 1). Overall quality of ground water for irrigation purpose was judged considering both EC and RSC (Sharma et al., 2008) (Table 2).

2.4. Geostatistical analysis and water quality mapping

Spatially auto correlated data that have a basic structure

Table 1: Criteria for classification of standard irrigation water

Criteria	Parameter	Value range	Suitability for irrigation
EEC classification (Lloyd and Heathcote, 1985)	RSC (meq l^{-1})	<1.25	Suitable
		1.25–2.5	Marginal
		>2.5	Unsuitable
USSL (Richards, 1954)	EC (dS m^{-1})	<0.25	Excellent
		0.25-0.75	Good
		0.75-2.25	Permissible
		2.25-4.0	Doubtful
		>4.0	Unsuitable



Map 2: Spatial variability maps for (a) pH (b) EC (c) Total hardness (d) Sodium (e) Potassium (f) Carbonate+Bicarbonate (g) Chloride (h) Sulphate (i) RSC (j) SAR

Table 2: Rating limits for evaluating suitability of ground water for irrigation in Punjab

Category		Sub-Category	EC (dS m^{-1})	RSC (me l^{-1})	Suitability for Irrigation
I. GOOD	I.	Good (Non-saline and non-sodic)	<2.0	<2.5	Suitable for all conditions
II. MARGINAL	II.a	Slight to moderately saline	2.0–4.0	<2.5	Suitable for coarse textured soil/salt tolerant crops with periodic monitoring of salt accumulation in soils.
	II.b	Moderate to highly saline	4.0–6.0	<2.5	Suitable after mixing with canal water.
	II.c	Slight to moderately sodic	<2.0	2.5–5.0	Suitable with recommended gypsum application
	II.d	Moderate to highly sodic	<2.0	5.0–7.5	Gypsum application
	II.e	Slight to moderately saline-sodic	2.0–4.0	2.5–5.0	Suitable after mixing with canal water and recommended gypsum application
III. POOR	III.a	Slight to moderately saline-moderate to highly sodic	2.0–4.0	5.0–7.5	Unsuitable for irrigation
	III.b	Extremely sodic	<4.0	>7.5	
	III.c	Extremely saline	>6.0	<2.5	
	III.d	Highly saline-sodic	>4.0	>5.0	

or spatial patterns can be handled well with geostatistics (Isaaks and Srivastava, 1989) and can be manifested in (semi) variogram analysis. (Semi) variogram is a characterization of the spatial correlation of the variables under study and indicates the relationship between the lag distance on the horizontal axis and the semi-variogram value on the vertical axis. The semi-variogram value increases from low to high values indicating higher spatial autocorrelation at the small lag distance (Nayanaka et al., 2010). Theoretically, to calculate the semi-variogram, the following formula is commonly used:

$$Y(h) = \frac{1}{2n\,(h)} \sum_{i=1}^{n\,(h)} [Z(xi) - Z(xi+h)]^2 \quad \text{.......................................(3)}$$

Where, γ(h) is the semi-variogram value for the lag distance (h), n(h) is the total number of the variable pairs separated by a lag distance (h), and Z(x) is the value of the variable.

Geostatistical interpolation (Kriging) was used to map spatial distribution of major quality parameters (pH, EC, total bi-carbonate, total hardness, sodium, chloride content, RSC, SAR and) in Geostatistical Analyst Tool in Arc Map 1. Exploratory data analysis was performed to explore the data under study to check data consistency, removing outliers and identifying statistical distribution where data came from. Data transformation was executed (wherever required) before generating prediction surface to reduce the skewness of the dataset and increase validity. Different types of Kriging in combination of suitable models (Johnston et al., 2001) were used to generate spatial variability maps for each of the parameters. Spatial dependence of groundwater quality parameters was judged on the basis of the classification suggested by Nayanaka et al., 2010. Area under various levels of salinity and alkalinity was calculated from the prediction surface. Finally, water quality map of Muktsar district was generated by uniting spatial variability maps for EC and RSC in Analyst Tool in Arc Map and area under different categories of water was computed. Simple statistics for each of the parameters was calculated for individual blocks and whole district.

3. Results and Discussion

3.1. Status of irrigation water quality in Muktsar district

The values of all the quality parameters widely varied within the district, even within the blocks (Table 3) due to the differences in the strata feeding a particular tube-well. Ground

Table 3: Block wise chemical characteristics of ground water samples in Muktsar district

Parameters	Range of values	Blocks				District
		Muktsar	Malout	Lambi	Kot Bhai at Gidderbaha	
pH	Minimum	7.05	6.93	7.42	7.65	6.93
	Maximum	8.48	8.28	8.45	8.55	8.55
	Mean	-	-	-	-	-
	SD	-	-	-	-	-
EC (dS m^{-1})	Minimum	0.35	0.44	0.77	0.75	0.35
	Maximum	7.35	16.92	19.61	13.60	19.61
	Mean	2.61	3.16	7.00	5.83	4.53
	SD	1.74	3.60	4.56	2.99	3.73
Ca^{2+}+ Mg^{2+} (me l^{-1})	Minimum	2.60	2.35	2.19	0.76	0.76
	Maximum	26.60	40.39	30.31	10.83	40.39
	Mean	9.64	9.24	9.12	6.18	8.64
	SD	5.66	7.82	6.64	2.65	5.98
Na^+ (me l^{-1})	Minimum	0.65	0.43	0.65	0.50	0.43
	Maximum	65.41	211.65	51.99	53.74	211.65
	Mean	20.06	26.87	19.63	18.93	20.96
	SD	16.88	42.79	13.42	12.48	22.63
K^+ (me l^{-1})	Minimum	0.07	0.07	0.07	0.09	0.07
	Maximum	1.52	1.00	1.08	0.59	1.52
	Mean	0.45	0.39	0.33	0.28	0.37
	SD	0.35	0.22	0.17	0.13	0.25

Table 3: Continue...

Parameters	Range of values	Blocks				District
		Muktsar	Malout	Lambi	Kot Bhai at Gidderbaha	
CO_3^{2-}+HCO_3^- (me l^{-1})	Minimum	2.00	3.00	2.49	2.74	2.00
	Maximum	12.00	14.00	15.05	16.03	16.03
	Mean	7.18	9.32	7.41	7.59	7.71
	SD	2.42	3.36	3.18	3.24	3.06
Cl^- (me l^{-1})	Minimum	1.25	1.25	0.96	1.20	0.96
	Maximum	34.32	71.76	26.16	19.92	71.76
	Mean	8.42	9.10	9.23	6.98	8.42
	SD	7.42	14.76	7.34	4.43	8.71
SO_4^{2-} (me l^{-1})	Minimum	0.05	0.25	0.05	0.19	0.05
	Maximum	11.84	10.40	12.71	10.57	12.71
	Mean	3.09	2.74	4.66	4.01	3.62
	SD	2.83	2.32	3.35	2.79	2.94
RSC (me l^{-1})	Minimum	-16.51	-13.42	-14.36	-5.90	-16.51
	Maximum	7.33	16.02	10.21	15.27	16.02
	Mean	-2.08	2.23	-0.42	1.42	-0.10
	SD	5.61	5.59	6.14	4.65	5.74
SAR	Minimum	0.54	0.40	0.58	0.34	0.34
	Maximum	20.50	34.44	21.66	45.27	45.27
	Mean	7.25	10.06	9.26	11.47	9.23
	SD	5.49	8.54	5.29	8.37	6.95

water reaction was tested to be near neutral in all the blocks of Muktsar district and the value ranged from 6.93–8.55. Ground water salinity was observed in all the blocks of the district with varying extent. Mean EC value was found to be above safe limit (2 dS m^{-1}) in all the blocks. RSC value was worked out to be positive in Malout and Kot Bhai at Gidderbaha block indicating dominance CO_3^{2-}+HCO_3^- over Ca^{2+}+Mg^{2+} and it was negative in Muktsar and Lambi blocks. Variability of other parameters within the blocks and district has been represented in Table 3.

3.2. *Spatial variability mapping*

Logarithmic data transformation was executed for dataset pertaining to EC, calcium and magnesium, sodium, potassium and chloride content in ground water to reduce skewness and increase validity, whereas, no transformation was needed for other parameters (Table 4). Spatial distribution of different ground water quality parameters for irrigation purpose was mapped using geostatistical interpolator (Kriging). Types of kriging used, its combination with different models and associated statistical details are presented in Table 4. Spatial dependence of each of the parameters was judged from nugget and sill value of the variogram model (Table 4). Spatial dependence of all the parameters was found to be moderate except carbonate and bicarbonate content where it was very strong (10.79%). Weaker the spatial dependence of the dataset larger the nugget effect in the semi-variogram model which may be due to the high micro scale variation and error (Santra et al., 2008).

Correlation coefficient (R^2) between the observed value and model predicted values for each of the parameters was found to high for all the parameters except total hardness where R^2 value was Comparatively poor (Table 4). Prediction surface generated for each of the ground water quality parameters are presented in Map 2 (a-j).

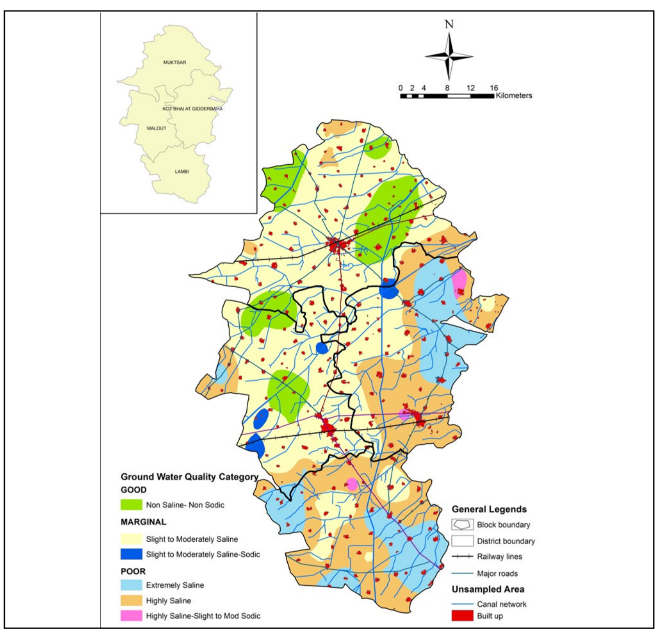
In terms of salinity, ground water was not excellent or even good (Table 1) in any part of the district. In 47353.6 ha area, ground water EC was found only within permissible limit, whereas it was found to be doubtful and unsuitable in 107835 and 108411 ha area, respectively. High salinity in ground water of Muktsar has also been reported earlier by Water Quality Assessment Authority, Govt. of India. Ground water reaction was within neutral range probably because of such high salinity. Ground water was tested to be safe in terms of sodicity in major part of the district (349385.0 ha).

3.3. *Delineation of water quality zones*

Ground water salinity was identified to be the major constraints in Muktsar district (Map 3). It was found to be slight to moderate, high and extreme in 124574, 71670.9 and

Table 4: Methods used for mapping spatial variability of ground water quality parameters for irrigation and associated statistical details

Statistical parameters	Water quality parameters				
	pH	EC	$Ca^{2+}+Mg^{2}$	Na^{+}	K^{+}
Transformation	None	Log	Log	Log	Log
Kriging type	Ordinary	Simple	Simple	Simple	Simple
Model used	Spherical	Exponential	Gaussian	Exponential	Circular
Nugget	0.06016	0.28	0.2	1.00230	0.180358
Partial Sill (C)	0.14672	0.43	0.21	0.41722	0.21555
Nugget/Sill	29.08	39.43	48.78	70.60	45.554
RMSE	0.29000	3.33057	5.5405	23.12922	0.23109
Spatial dependence	Moderate	Moderate	Moderate	Moderate	Moderate
Range (m)	0.292933	0.14686	0.103812	0.146928	0.12830
R^2	0.823	0.82	0.51	0.556	0.727
Statistical parameters	Water quality parameters				
	$CO_3^{2-}+HCO_3^{-}$	Cl^{-}	SO_4^{-2}	RSC	SAR
Transformation	None	Log	None	None	None
Kriging type	Simple	Simple	Simple	Simple	Simple
Model used	Exponential	Circular	Exponential	Circular	Exponential
Nugget	1.00286	0.4	4.629242	15.0	12.50221
Partial Sill (C)	8.28851	0.36650	3.93551	14.5873	19.878
Nugget/Sill	10.793	52.18	0.5404	50.69	38.61
RMSE	3.00706	8.55422	2.73148	5.614	5.8134
Spatial dependence	Strong	Moderate	Moderate	Moderate	Moderate
Range (m)	0.04767	0.03836	0.10903	0.03165	0.3
R^2	0.823	0.82	0.51	0.556	0.727



Map 3: Ground Water Quality map for Muktsar district

35136.3 ha area, respectively covering 47.3, 27.2 and 13.3%. of TGA of the district. Slight to moderate ground water sodicity was prevalent in only 1.6% of TGA of the district along with varying levels of salinity. In only, 27857.5 ha area ground was tested to be good for irrigation purpose.

4. Conclusion

Ground water salinity was identified to be the major constraints in Muktsar district. High to extreme ground water salinity (EC>4 dS m^{-1}) was prevalent in mainly Kot Bhai at Gidderbaha and Lambi blocks, whereas slight to moderate salinity was observed in Muktsar and Malout blocks. Good quality ground was found mainly in Muktsar block. In only, 27857.5 ha area ground was tested to be good for irrigation purpose. Slight to moderate sodicity in ground water was found in small patches in Kot Bhai at Gidderbaha and Malout blocks.

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