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Article

Hydrochemical Appraisal of Groundwater Quality for Managed Aquifer Recharge (MAR) in Southern Punjab, Pakistan

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Abstract

Water quality assessment is crucial for the sustainable use and management of groundwater resources. This study was carried out in the irrigated plains of Vehari District, Punjab, Pakistan, to evaluate groundwater suitability for a managed aquifer recharge (MAR) project. Twenty-three groundwater samples were collected in June 2021 from an area of 1,522 km² and analyzed for major physicochemical parameters including electrical conductivity (EC), total dissolved solids (TDS), pH, turbidity, calcium (Ca), magnesium (Mg), chloride (Cl), alkalinity (Alk), bicarbonate (HCO₃⁻), hardness, potassium (K), sulphate (SO₄²⁻), sodium (Na), and nitrate (NO₃⁻). Water quality was assessed using WHO and PID standards, alongside derived hydrochemical indices such as sodium percentage (%Na), Kelley's ratio (KR), sodium adsorption ratio (SAR), residual sodium carbonate (RSC), and the water quality index (WQI). The dataset was interpreted using geo-statistical, geospatial, multivariate, and correlation analyses. Cation and anion dominance followed the order Na⁺ > Ca²⁺ > Mg²⁺ > K⁺ and HCO₃⁻ > SO₄²⁻ > Cl⁻ > NO₃⁻. WQI results showed that 35% of samples indicate "poor," 50% "very poor," and 15% "unsuitable" drinking-water quality. However, irrigation suitability indices confirmed that groundwater is generally acceptable for agricultural use, though unfit for drinking. The outcomes of this study provide essential insights for groundwater management in the region, where the Punjab Irrigation Department (PID) has initiated a MAR project. Considering that the irrigation sector is the major groundwater consumer in the area, the compatibility of groundwater and surface water quality supports the implementation of MAR to enhance agricultural sustainability.

Keywords: groundwater; quality index; geospatial; geo-statistical; Vehari; Pakistan

1. Introduction

The fundamental need of humans is water, and groundwater is the major source for drinking (He et al., 2015; Morris, 2003). Control over the water resources has remained central all rulers globally (Zakir-Hassan, Allan, et al., 2023). It is considered a major source of drinking water due to its purified nature in soil column which is approximately half of the drinking water supply globally (Olufemi, 2010; Snousy et al., 2021). About one-third of global irrigation requirements are met by groundwater. The mainstay of 50% of world's population for the drinking and irrigation is groundwater by consuming 30% of freshwater reserves of the world (Siebert et al., 2010; Smith et al., 2020; Snousy et al., 2021; Zektsar, 2013) while the remaining 70% is in the form of the ice caps, glaciers, and the other water bodies i.e., rivers and streams (Chandnani et al., 2022; Punthakey et al., 2021).

About 2.2 billion people depends solely on groundwater to fulfil their basic water needs and supply of good quality drinking water (Adimalla and Qian, 2019; Chique et al., 2020; Murphy et al., 2017). Groundwater underpins global food security as about 40% of global food is produced from groundwater (Leslie et al., 2022). Recent infrastructure developments and global population increase has significantly increased the groundwater consumption. In under-developing countries like Pakistan, people in rural and urban areas use groundwater for irrigation and drinking. Over 70% of Pakistan's rural population has no access to safe drinking water. Groundwater is being extensively consumed in the country due to the availability of cheap technologies of groundwater extraction and better quality than surface water (Shaji et al., 2021). Further floods are a source of aquifer recharge and improved groundwater quality (Zakir-Hassan et al., 2021).

The direct and indirect disposal of industrial wastes and effluents into the environment and water bodies has significantly deteriorated the groundwater quality in the last few decades (Karangoda and Nanayakkara, 2023). Consuming polluted water is a severe concern to human health, and reclaiming the aquifer is difficult. (Gao et al., 2020; Vaithyanathan and Ravichandran, 2017). About 39,00,0 children die every year due to waterborne diseases (Solangi et al., 2019; Vaithyanathan and Ravichandran, 2017). It is a basic right for everyone to get the good quality of water for essential of their natural life (Saha et al., 2018; WHO, 2011). Multiple organizations have developed their standards based on chemical, physical and biological properties to evaluate the suitability of water, the most followed standards are of World Health Organization (WHO, 2011; Adimalla and Qian, 2019; Norouzi and Moghaddam, 2020). Knowledge of irrigation water quality is critical to understand management for long-term productivity.

In arid/semi-arid regions of the world, water quality has deteriorated due to increase in salinity problems in large aquifers of coastal areas impacted by sea water intrusion (Bahir et al., 2017; Bahir et al., 2018; El Mountassir et al., 2020; Jalali, 2007). Extra exploitation of groundwater has resulted in movement of saline water in to aquifer (Adimalla and Qian, 2019). Groundwater quality also depends upon topography, precipitation and natural minerals in lithology of the area (Aly, 2015; El Mountassir et al., 2020; Emenike et al., 2017; Sappa et al., 2015). Once the contaminants are leached down in the aquifer, their impacts on groundwater quality depend upon its chemical and biological properties, structure and other soil/rock properties (Custodio, 2012). Since a single element cannot depict the overall water quality therefore multiple parameters are brought under analysis i.e., pathogens, fluorides, nitrate, arsenic, chlorine, other metals.

Water Quality Index (WQI) explains a comprehensive picture of water quality of a specific region. Numerous researchers have used the WQI theory to obtain a single indicator and developed WQIs for irrigation and drinking (Kachroud et al., 2019; Singh et al., 2013; Swaroop Bhargava, 1983; Tiwari et al., 2017; Tyagi et al., 2020; Wang et al., 2015). Water quality index parameter initially developed by Horton in 1965 has been used by different researchers (Adimalla and Taloor, 2020; Palit et al., 2018; Saleem et al., 2016) and different approaches have been used to calculate WQI (Gidey, 2018; Mutasher et al., 2021; Nisa, 2018; Prabowo et al., 2021; Sharma et al., 2021; Srinidhi et al., 2021). Different numerical indices, graphics, plots, diagrams have also been developed in the field of hydro geochemistry to interpret the suitability of groundwater for different uses. MAR is the process under which surplus water is stored underground for future use. Its benefits include improving groundwater quality and level. A comprehensive review of water quality monitoring and assessment in Pakistan has been carried out by (Kumar et al 2023); which revealed that tremendous rise in population, industrialization and agricultural activities are major threats for degradation of both surface and groundwater quality.

MAR and water banking are significantly important for water resources management (Hossain et al., 2019; Sherif et al., 2023). (Dillon et al., 2009; Page et al., 2010; Zakir-Hassan, 2023) define MAR as "*purposeful recharge of water to aquifers for subsequent recovery or environmental benefit*". MAR can be used to buffer against drought and changing or variable climate, as well as provide water to meet growing demands. Groundwater quality cannot be ignored during MAR for sustainable groundwater management (Barry et al., 2017; Ross, 2022; Vanderzalm et al., 2015). During MAR, river

water, rainwater or wastewater can be used a source (EPA_Victoria, 2009; Vanderzalm et al., 2015) for transferring to the aquifer (sink) through some managed techniques. Soils and water get contaminated by using the wastewater for irrigation of vegetable and other crops in urban areas which can be hazardous for the MAR schemes (Natasha et al., 2022; Zakir-Hassan, Punthakey, Hassan, Shabir, et al., 2022). During this whole process of MAR, it is imperative that quality of waters of both the source and the sink must be suitable for the intended purpose of the MAR (Leslie et al., 2022; Page et al., 2010; Pavelic et al., 2022). Due to high importance of irrigation water supplies and drinking water quality, there is a dire need to check the different water quality parameters for its better utilization, management, protection, and sustainable development (Zakir-Hassan, Punthakey, Hassan, & Shabir, 2022). This study has been performed to evaluate the current status of groundwater quality for its proper management, and to establish baseline data for a managed aquifer recharge project in the study area. Drainage effluents also pose adverse impacts on groundwater (Zakir-Hassan, Hassan, et al., 2022).

2. Materials and Methods

2.1. Study Area

The study was carried out in Vehari district of Punjab, Pakistan located at 29.9719 °N, longitude 72.4258 °E with an area of 1371 km² bounded with Pakpattan Islam Link Canal, Sindhnai Mailsi Bahawal Link (SMB-link) Canal, Pakpattan Upper Canal, and River Sutlej on Eastern, Western, Northern and Southern sides, respectively. Canal network in Indus River Basin is a major source of water supply for irrigation as well for recharging the large aquifer (Zakir-Hassan, Kahlowan, et al., 2023). The area is around 140 m above mean sea level and comprises rural and urban localities. The population of district Vehari is about 2.9 million with growth rate of 2.23%, and the majority of people are linked with agriculture for their livelihood (GOP, 2018; Sindhu, 2010). Vehari is food basket for the province as well as being called the city of cotton. Groundwater levels have fallen down to 15 to 25 m below the land surface and there is sufficient potential for storage of floodwater (Zakir-Hassan et al., 2024). In addition to groundwater, canal water is also supplied through a network of canals. Map of study area with sampling locations is shown in Figure 1. Primarily, groundwater is used for irrigation in the study area as canal water is not sufficient to meet the irrigation and drinking requirements. Managed aquifer recharge is dire need of the study area for sustainable use of groundwater (Zakir-Hassan et al., 2025).

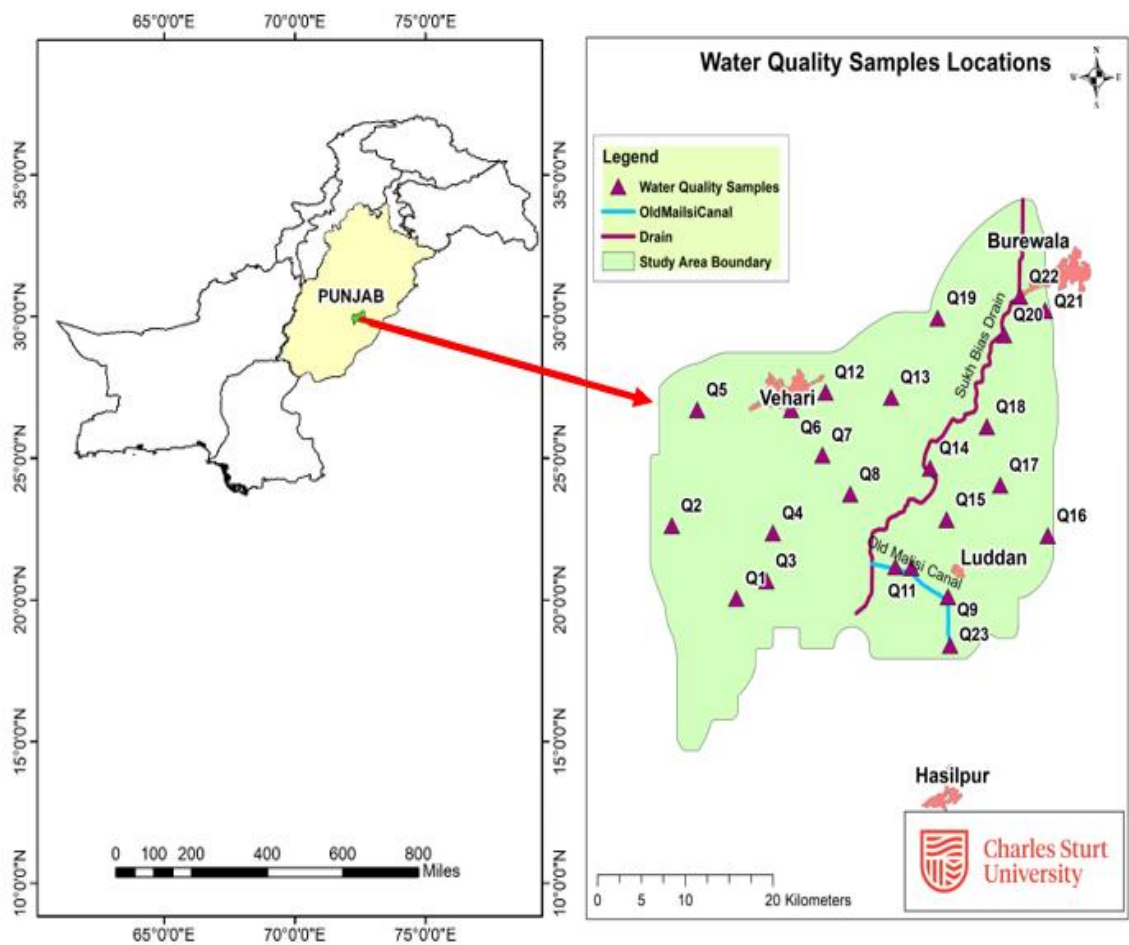


Figure 1. Map of study area showing major features and sampling locations.

2.2. Water Samples Collection and Lab Analysis

Sampling is a process to collect a portion of material small enough in volume to be transported and large enough for analysis (APHA, 2021). Total 23 water samples were collected from field during May and June 2021 as per standard procedures and methods prescribed by American Public Health Association (APHA, 2021). Some of the parameters like temperature, EC, TDS, pH, depth of bore, well locations, ground elevations, static water levels, source of water sampling (like tube wells, drain, canal, river) were collected in field during sampling using portable multi-parameter devices. These devices were calibrated as per prescribed standards before use in field. Samples were collected, sealed at site, packed in containers and transported to lab(Zakir-Hassan, 2023) . It was ensured that samples are kept at cool place (4°C) until transportation to lab. Most of the groundwater samples have been taken from tube wells or turbines from a depth varying from 70 to 140 m with an average of 96 m. Equipment/ materials used in the field sampling were sampling bottles with lids, waterproof marker-pen for writing, labels for coding the samples, EC, pH and temperature portable meters, PPEs (gloves, field shoes, hats, drinking water), Sample containers for stacking samples, sealing tapes, field umbrella, PC tablet and field notebook/performa for recording codes and other details of samples. Samples were analyzed at laboratories of Irrigation Research Institute (IRI) and Pakistan Council of Research in Water Resources (PCRWR) as per stanadrd procedures enlisted in Table S1 in supplementary information. The overall methodology for groundwater quality analysis is depicted in Figure 2.

Table 1. Parameters estimation (Chin, 2013; Davis, 2010).

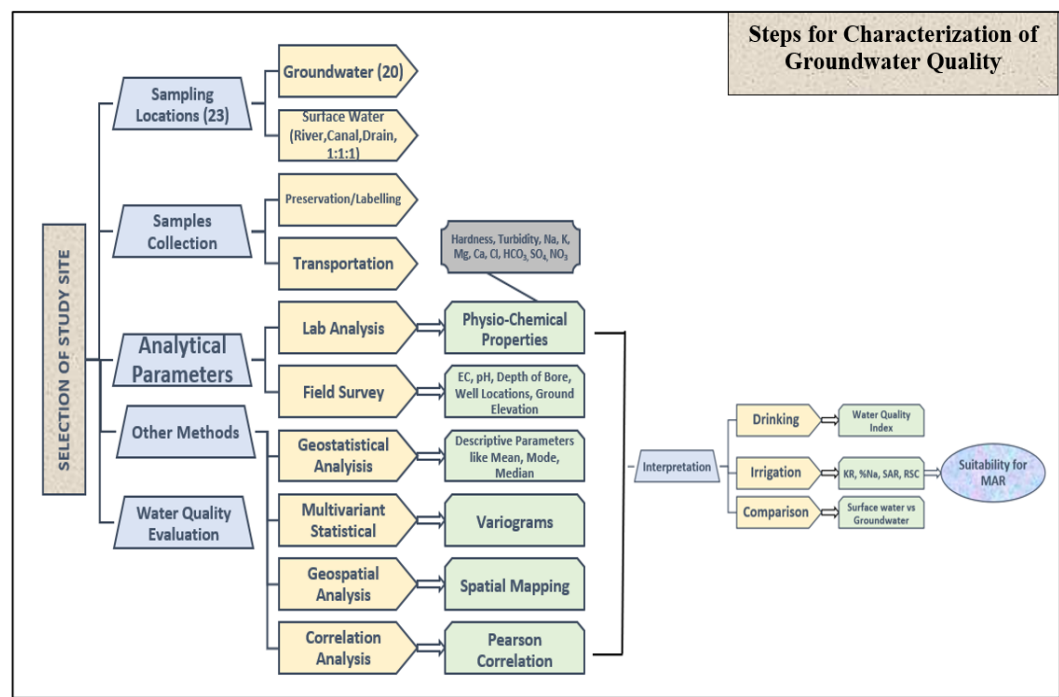


Figure 2. Methodology for evaluation of groundwater quality for MAR project.

2.3. Methods of Interpretation of Water Quality

General descriptive analysis was performed to calculate mean, standard error, standard deviation, coefficient of variance, minimum and maximum values using MS Excel (Solangi et al., 2019). Charge balance error (CBE) was calculated using Equation 1 (Adimalla & Qian, 2019; Adimalla & Taloor, 2020; Snousy et al., 2021).

$$CBE = \frac{[\sum \text{cations} - \sum \text{anions}]}{[\sum \text{cations} + \sum \text{anions}]} \times 100 \tag{1}$$

Where, concentrations of all cations (Na⁺, K⁺, Mg²⁺, and Ca²⁺) and anions (Cl⁻, HCO₃⁻, SO₄²⁻, and NO₃⁻) are in milliequivalent per liter (meq/l). CBE for all samples have been plotted in Figure S1. All values - except one value - fall within ±5% which are within permissible limit (Adimalla, 2021; Gao et al., 2020). One value which exceeds ±5%, is within the acceptable limit of ±10% (Adimalla & Qian, 2019; Mohan & Krishnakumar, 2021). This indicates the accuracy of lab analysis and reliability of results.

GS+ software was used to determine the variogram models, which is generally used to depict the variability between the spatially distributed data points. All the semi variogram models were analyzed and best fit semi variograms model were selected among spherical, exponential, Gaussian, and linear models. Pearson’s correlation analysis has been performed to estimate correlation coefficients which show the dependency of each parameter with the other parameters. This p-value test was done using the Stistica-10 at 0.01, 0.05 and 0.001 significant levels. Generally Inverse Distance Weighted Interpolation (IDWI) technique is used to spatially plot the hydro-chemical parameters of groundwater (Mohan & Krishnakumar, 2021). Standards prescribed by WHO & PID were employed to check the suitability of the water quality (Zakir-Hassan, 2023) and (WHO, 2011).

Water quality index (WQI) is considered one of the best methods to analyze and depict the quality of water, which can be used by policy and decision makers for both surface and groundwater (Adimalla & Qian, 2019; Saleem et al., 2016; Srinidhi et al., 2021). This index gives rating of water quality ranging from 0 to 100 and takes into account different parameters of a water samples and reflects the combined effect of large number of water quality parameters into a single value (Saleem

et al., 2016). Equations by using the weighted arithmetical index method for calculation of WQI (Nisa, 2018; Ruhela et al., 2021; Saleem et al., 2016; Sharma et al., 2021) are as under.

$$WQI = \frac{\sum W_n Q_n}{\sum W_n} \quad (2)$$

$$W_n = \frac{K}{S_n} \quad (3)$$

$$K = \frac{1}{\frac{1}{S_1} + \frac{1}{S_2} + \frac{1}{S_3} + \dots + \frac{1}{S_n}} \quad (4)$$

$$Q_n = \frac{V_n - V_o}{S_n - V_o} \times 100 \quad (5)$$

where, w_n is unit weight factor, S_n is standard desirable value of n th parameter, Q_n is sub-index, V_n is the mean concentration of n th parameter, V_o is the actual value of parameters in pure water ($V_o = 0$ mostly), and WQI is the water quality index.

2.4. Suitability of Groundwater for Irrigation

Multiple parameters like %Sodium, (%Na), Kelly Ratio (KR), Sodium Adsorption Ratio (SAR), and Residual Sodium Carbonate (RSC) were calculated to evaluate the suitability of groundwater for irrigation. The evaluated parameters were plotted using ArcGIS 10.6. Sodium percentage (Na %) was calculated by the following formula (Adimalla, 2020; Wilcox, 1955):

$$Na\% = \frac{Na^+}{Ca^{2+} + Mg^{2+} + Na^+ + K^+} \times 100 \quad (6)$$

All concentrations are in meq/l. This percentage indicates the Sodium hazard in the water, if found excessive it reduces the soil permeability. If this percentage is less than 20, water is excellent for irrigation use, up to 40 it is good, 40-60 permissible and more than 60 is doubtful.

Kelley in 1963 proposed a relation between sodium and alkaline earths (Adimalla, 2020). It is calculated using following equation: -

$$KR = \frac{Na^+}{Ca^{2+} + Mg^{2+}} \quad (7)$$

If $KR > 1$, water is safe for irrigation and if $KR < 1$, water is not safe for irrigation (Adimalla, 2020).

Residual Sodium Carbonate (RSC) is used to predict the additional sodium hazard associated with $CaCO_3$ participation and is another alternative measure of the sodium contents in relation with calcium and magnesium. This can be calculated as:

$$RSC = (CO_3^{2-} + HCO_3^-) - (Ca^{2+} + Mg^{2+}) \quad (8)$$

where, all concentrations are in parts per million (ppm).

Sodium adsorption ratio (SAR) is an easily measured property that gives information on the comparative concentrations of sodium, calcium and magnesium (Hopkins et al., 2007). The SAR can be calculated as:

$$SAR = \frac{[Na^+]}{\sqrt{[Ca^{++}] + [Mg^{++}]}/2} \quad (9)$$

where, all concentrations are in mill equivalent per liter (meq/l)

3. Results and Discussions

Figure 3.

3.1. Geo-Statistical Analysis

The results of various parameters of descriptive analysis are presented in Table 1. Measurements of various parameters exhibited tolerable variation among sites although there was a great variation in total dissolved solids. Only descriptive statistics relevant to sample size, mean and standard error are presented to give an indication of sampling intensity and variation of observations. Singh et al.,

(2022) has provided an indication of geostatistical analysis in groundwater interpretation. It analyzes the spatial patterns of values associated with different locations in a landscape.

Table 1. Results of descriptive geo-statistics of groundwater samples in study area.

Parameters	Alk (ppm)	HCO ₃ (ppm)	Ca (ppm)	Cl (ppm)	EC (μS/cm)	Hardness (ppm)	Mg (ppm)	pH	K (ppm)	SO ₄ (ppm)	Na (ppm)	TDS (ppm)	Turbidity (NTU)	Nitrate (ppm)	Arsenic (ppb)
Minimum	4	200	36	19	703	180	7	7	4	52	65	373	5.1	0.04	6.2
Maximum	12	600	208	451	4650	1040	126	8	13	1320	580	2887	18.1	0.9	1223
Mean	6.8	342	95.7	78.1	1340	390	36.2	7.5	7.3	245	136	805	10.5	0.2	29.3
Standard Deviation	2.1	106	41.8	93.2	872.7	180.7	26.8	0.2	2.0	261	113	531	2.5	0.2	29.4
Standard Error	0.46	23.1	9.1	20.3	190.4	39.4	5.9	0	0.4	56.9	24.6	116	0.55	0.05	6.4
Coefficient of variation(CV)%	27	27	24	22	22	21	22	20	23	21	22	21	19	24	25

Major cations and anions in groundwater samples have been plotted to show their abundance in Figure 3 & Figure 4 which indicates the dominant cations are Na and Ca, while dominant anions are HCO₃ and SO₄.

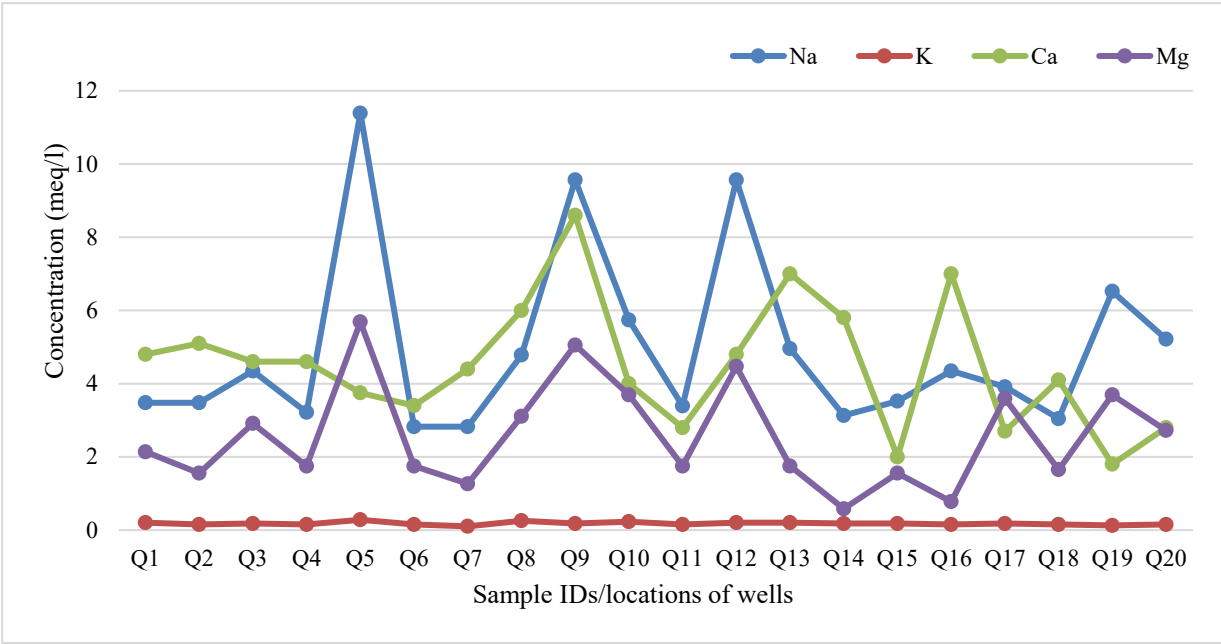


Figure 3. Spatial trends of cations in groundwater samples (n = 20).

It was revealed from the results of 20 water quality samples that point 5 and 12 are highly contaminated with Na. It was further observed that these points were located near Vehari City which is a source of domestic and industrial effluents. Descriptive analysis has indicated that the abundance of cations based on their mean values in ppm, both in surface as well as groundwater samples are in the order: $\text{Na}^+ > \text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+$. It indicates Na is dominant salt in water samples in the study area.

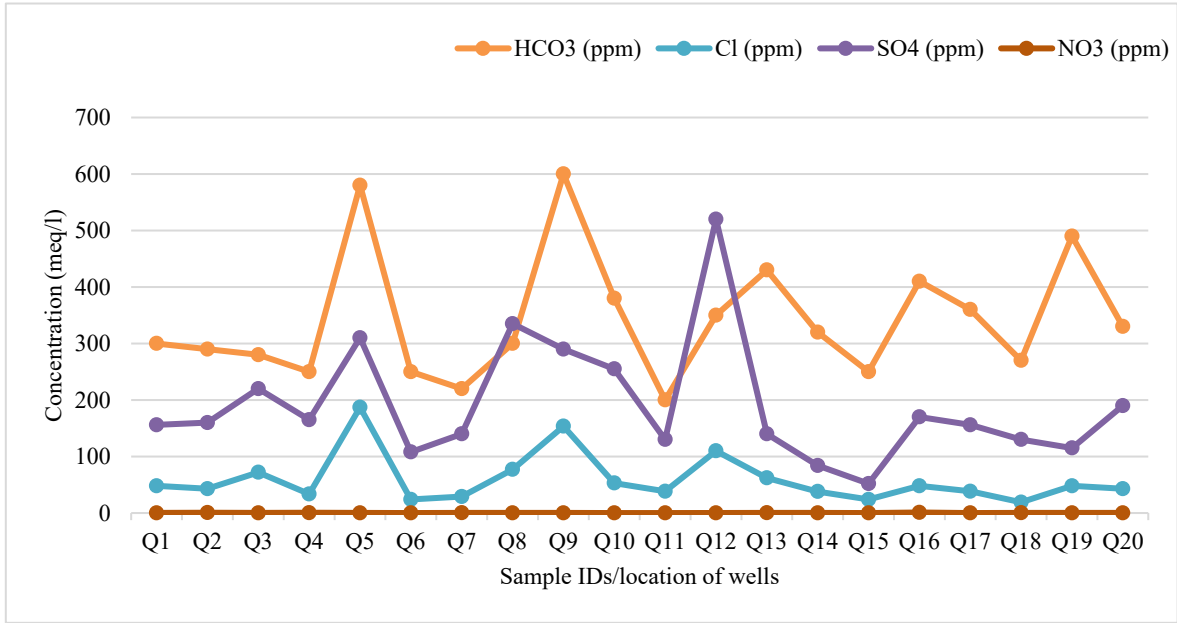


Figure 4. Spatial trends of anions in groundwater samples.

It was noticed that point 5 and 9 are highly dominated with HCO_3^- concentrations while point 12 was dominant in SO_4^{2-} . It indicates that Vehari city (Urban Centre) is a source of contamination for groundwater and after that poor results were obtained near Ludden (thickly populated town). Descriptive analysis has indicated that the abundance of anions based on their mean values in ppm, both in surface as well as groundwater samples are in the order; $\text{HCO}_3^- > \text{SO}_4^{2-} > \text{Cl}^- > \text{NO}_3^-$ respectively. Figures 6 and 7

Lithological and anthropogenic activities are the main sources of presence of Na in water. Nominal amount of Na is suitable for blood circulation and muscles but excessive intakes have reported death cases (Malik & Sugandh, 2022). The average Na concentration of 20 water samples in study area was measured as 136.3 ppm which lies within the permissible limits set by PID. Similarly, presence of Ca in water is due to dissolution of dolomite, marble and gypsum. Limited quantity of Ca in water is helpful for muscles and bones. The average Ca concentration in the study area was calculated as 95.7 ppm which was slightly higher than the recommended or suitable range and lies in marginal category. Also, the concentration of Mg and K were slightly higher than the recommended levels as the mean values were 36.3 and 7.3 ppm as compared to standards limits i.e., 30 and 7 ppm respectively.

Bicarbonate (HCO_3) is mainly responsible for reducing/neutralizing pH of water. Areas rich in limestone have excessive HCO_3 in their waters. The average concentration of HCO_3 in study area was 341.9 ppm which was a bit higher than the standard level of 200 ppm (WHO 2011). Generally the atmospheric deposition and sulphate dissolution are the main source of presence of sulphate in water sample (Wang & Zhang, 2019). The average SO_4 concentration in study area was 245 ppm which was again a bit higher than the recommended level of 200 ppm. The concentrations of Cl and NO_3 were found under the standard limit.

3.2. Multivariate Analysis

To depict and analyze the spatial correlation among various parameters, variogram analysis was performed. Results showing type, statistical parameters, and spatial class for the best fitted variogram models for each physiochemical parameter are tabulated in Table 2. Results indicate that there is no spatial correlation for turbidity and potassium; for alkalinity and bicarbonate there is random correlation among the sampling points, but for other elements there is evidence of non-random correlation among the parameters.

3.3. Pearson Correlation Analysis

Pearson’s correlation factor (r) is a factor which associates the strength of correlation between two parameters. It has the value equal to 1, when a parameter is compared with itself, it shows perfect correlation – $r = 1$. Values of $r > 0.7$ or -0.7 indicate that the parameters are vigorously correlated, while values of the r from 0.5 to 0.7 or -0.5 to -0.7 depict reasonable correlation (Mohan & Krishnakumar, 2021). Results are presented in a tabular form called Correlation Matrix shown in Table 3. Values of positive correlation indicated the shared origin between the parameters and negative correlation indicated the diverse sources of origin (Mohan & Krishnakumar, 2021). According to p-value we can find the significance between different parameters. If the p-value is less than or equal to 0.001 and 0.01 then the co-relation is significant. If the p-value is greater than 0.05 then it is considered that there is no co-relation.

Table 2. Statistics of best fitted variogram models for different parameters.

Parameter	Best fitted Model	Range (m)	Nugget C_0	Sill C_0+C''	Partial Sill C''	Nugget % $100 \times C_0 / (C_0+C'')$	Spatial Class*	R^2
Alk	Exponential	0.06	2.497	4.995	2.498	50.01001001	W	0.021
HCO_3	Exponential	0.06	6230	12470	6240	50.04009623	W	0.021

Ca	Gaussian	0.04	1	1259	1258	99.92057188	S	0.354
Cl	Gaussian	0.05	1	1810	1809	99.94475138	S	0.297
EC	Spherical	0.08	100	248100	248000	99.95969367	S	0.203
Hardness	Spherical	0.07	1750	14430	12680	87.87248787	S	0.075
Mg	Gaussian	0.05	145.3	320.2	174.9	54.62211118	S	0.17
pH	Gaussian	0.07	0.0001	0.46	0.4599	99.97826087	M	0.347
K	Linear	0.21	2.62358	2.62358	0	0	S	0.026
SO ₄	Spherical	0.07	10	14420	14410	99.93065187	S	0.279
Na	Gaussian	0.05	327	3460	3133	90.54913295	S	0.317
TDS	Spherical	0.08	6700	80200	73500	91.64588529	S	0.166
Turbidity	Linear	0.21	8.57956	8.57956	0	0	W	0.122
NO ₃	Gaussian	0.06	0.0001	0.0407	0.0406	99.75429975	M	0.515

Table 3. Correlation matrix of different parameters.

	Alk	HC O ₃	Ca	Cl	EC	Har dnes s	Mg	pH	K	SO ₄	Na	T D S	Turb idity	N O ₃
Alk (pp m) HCO ₃ (pp m)	1***													
Ca (pp m)	0.35 1*	0.35 1*	1***											
Cl (pp m)	0.77 1***	0.77 1***	0.37 7*	1***										

EC (µS/cm)	0.84 8***	0.84 8***	0.43 8*	0.96 1***	1***								
Hardness (ppm)	0.72 2**	0.72 2**	0.76 4***	0.82 1***	0.88 5***	1***							
Mg (ppm)	0.69 6**	0.69 6**	- 0.02 2	0.81 7***	0.84 3***	0.629 **	1***						
pH	0.48 6*	0.48 6*	- 0.40 9	0.60 3**	0.51 3**	0.144	0.71 5**	1** *					
K (ppm)	0.40 6	0.40 6*	0.19 9	0.63 6**	0.58 5**	0.513 **	0.55 4**	0.4 52*	1** *				
SO ₄ (ppm)	0.35 6*	0.35 6*	0.30 6*	0.70 1**	0.75 3***	0.690 **	0.70 0**	0.3 33*	0.5 54*	1*** *			
Na(p pm)	0.81 7***	0.81 7***	0.19 5	0.92 6***	0.95 6***	0.721 ***	0.88 2***	0.6 58*	0.5 43*	0.73 4***	1***		
TDS (ppm)	0.78 ***	0.78 0***	0.44 3*	0.93 6***	0.98 5***	0.884 ***	0.83 5***	0.4 86*	0.6 03*	0.84 7***	0.94 5***	1* **	
Turbidity (NTU)	- 0.16	- 0.16	- 0.00 3	- -0.009 3	- 0.03 3	- 0.003	- 0.00 1	- 0.1 04	0.3 60*	0.17 4	0.00 3	0. 02 8	1***
NO ₃ (ppm)	0.00 1	0.00 1	0.41 2*	- 0.16 8	- 0.14 3	0.026 3	- 0.45 5	- 0.3 35	- 0.3 05	- 0.16 4	- 0.22 7	- 0. 12	- 0.141 *

* Correlation is significant at the 0.05 level (2-tailed). ** Correlation is significant at the 0.01 level (2-tailed). *** Correlation is significant at the 0.001 level (2-tailed).

As shown in Table 3, HCO₃ has perfect relation with Alk while NO₃ has weak relation with Ca. Ca has weak relation with Alk and HCO₃. Turbidity has no strong relation with any other parameter. TDS has strong relation with EC, Alk, HCO₃, Hardness, Mg and SO₄. Sodium (Na) has weak relation with Ca and K while strong relation with all other parameters. Whereas SO₄ has weak relation with alkalinity, HCO₃, Ca and pH, on the other hand exhibit moderate relation with Cl, hardness, and Mg; same is for potassium (K) has which has moderate relation with these three parameters. Mg has strong relation with Cl and EC. Hardness is vigorously correlated with alkalinity.

3.4. Subsurface Hydrogeology

Bore logs drilled by different organizations in the study area were analyzed to depict the subsurface hydrogeology of the study area. The surficial materials typically encountered along the bed of OMC, through which the surface water flows, are of variable thickness ranging from 1 to 3 m, mostly alluvial, generally comprised of water-deposited silt, silty sand, interspersed with silty clay. These materials rest on the underlying sandy aquifer throughout canal. The silt particles in the top layer are well-graded and generally not permeable. By considering the extent and geological make-up of the surficial materials, direct recharge of water from the ground 180 surface into the underlying sand aquifer through these materials are unlikely to be substantial due to the low hydraulic conductivity of the surficial materials. These findings suggest that to recharge the main groundwater aquifer effectively, it would require drilling and installation of injection/recharge wells at the project site to facilitate/accelerate water recharge from the ground surface into the more permeable underlying sandy aquifer (Zakir-Hassan, 2023).

3.5. Suitability of Groundwater for Drinking Purpose

The major use of groundwater in the study area is for irrigation applications but it is also being used for drinking. In urban area of Vehari city, Municipal Committee Vehari is pumping groundwater from a pump station nearby the Pakpatan Main Canal and transporting to the city to provide drinking water to the community. In rural areas, HUD & PHED have constructed rural water supply schemes (RWSS) to supply drinkable groundwater to the rural population. Some people are extracting groundwater directly through hand pumps and small submersible pumping units at household level. Groundwater is a major source of water for drinking and evaluation of its existing level of contamination is important for the human-health and other implications.

(Saleem et al., 2016) have described the use of WQI method of interpretation of groundwater quality, declaring it a fast, easy, and composite method. Similarly, (Pant et al 2023) have applied and WQI for river water quality analysis in India and found that this is a suitable method to characterize the water quality.

Table 4 depicts the classification of water for drinking and results of groundwater analysis in the study area. Geospatial plot of WQI interpolated into the whole study area is plotted in Figure 5 and the values of WQI for individual sampled wells are depicted in Figure 6.

Table 4. Classification of water based on water quality index for drinking purposes (Palit et al., 2018; Saleem et al., 2016; Solangi et al., 2019).

WQI Range	Type of Water/Status	Class	No of samples (%)
0-25	Excellent	I	-
26-50	Good	II	-
51-75	Poor	III	7 (35%)
76-100	Very poor	IV	10 (50%)
>100	Unfit for consumption	V	3 (15%)

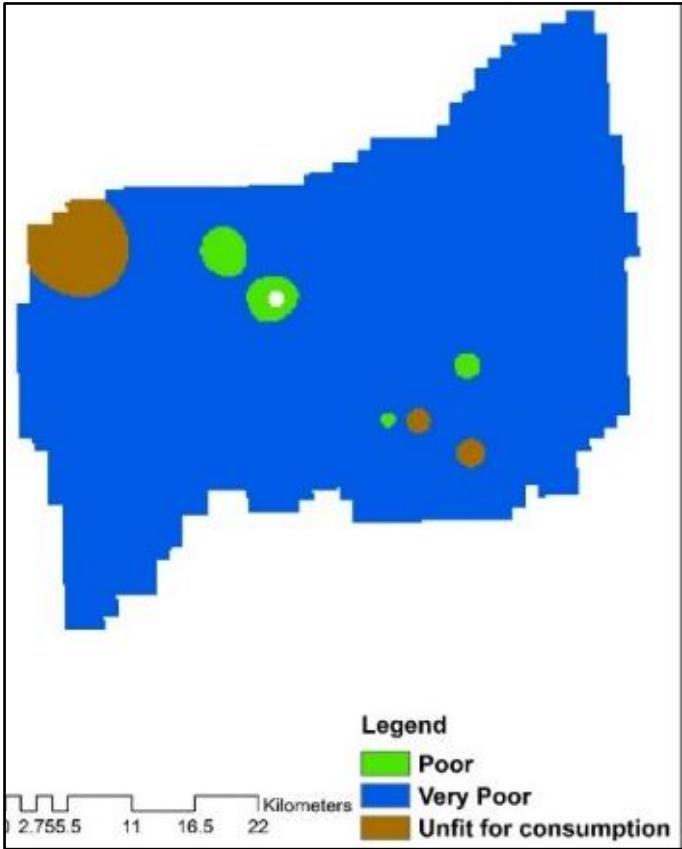


Figure 5. Plot of WQI depicting suitability of groundwater for drinking using IDW.

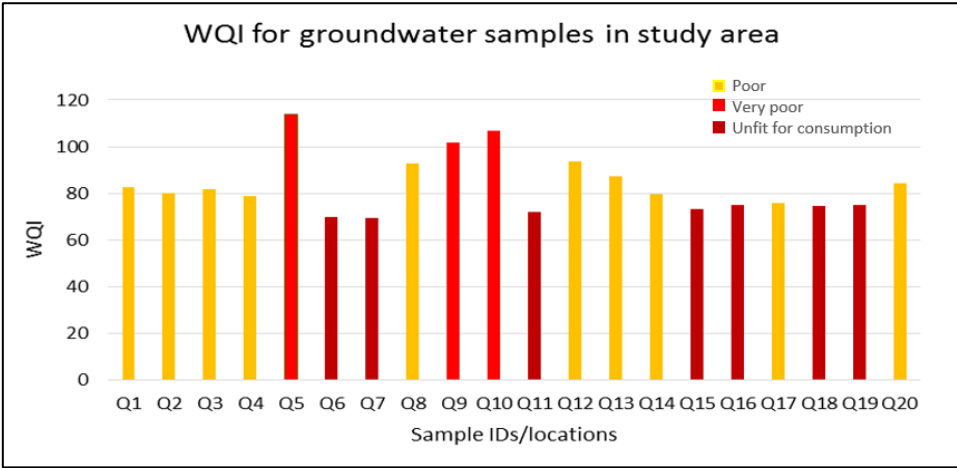


Figure 6. Water quality index for groundwater samples in study area.

WQI reflects the integrated effect of measurements obtained for individual element. There is a part of catchment in which many individual elements are not suitable for quality assessment. Integration of individual elements into a single index – WQI - suggests that there are no parts of existing aquifer that has water in a better condition than “poor”. It was revealed that 35% samples fall under poor, 50% under very poor, and 15% under unfit for consumption class and none of sample falls under the class I and II (excellent and good) of WQI as depicted in Table 4. As such, it is concluded that groundwater in the aquifer is not suitable for human consumption. Tube well 5 exists in the vicinity of Vehari city, where the water quality is unfit for consumption (Fig 6) and is not suitable for drinking. Similarly, the other two wells (Q9 and Q10), which too exhibit the groundwater unsuitable for drinking, fall in the vicinity Ludden. Ludden is a bigger, populated rural center which seems to be a source of contamination for groundwater. It is concluded that apparently the municipal

effluents are the source of groundwater contamination, as the points falling under class V of WQI are located near the populated localities. Other wells falling under comparatively more populated centers. The rest of the wells showing the adverse quality are located near the Sukh Beas Drain (SBD) passing through the study area.

Human health may face sever issues due to consumption of this contaminated water (Amarachi et al 2023). Contaminated groundwater in an aquifer may cause adverse impacts on the human health in the nearby surrounding areas as well (Bento et al 2023). In the study area, as groundwater is not suitable for human consumption, the health of the population in the area is at risk. Therefore, proper monitoring, evaluation, and management of water quality is of paramount importance. Similar findings have been reported by (Iqbal et al 2021).

3.6. Suitability of Groundwater for Irrigation

Groundwater quality for irrigation purposes has been evaluated by analyzing the values of individual analytical parameters and by calculating some integrated parameters. Three classes viz: suitable, marginal and un-suitable have been used on the basis of WHO and PID standards for suitability of groundwater for irrigation (WHO 2011; Zakir-Hassan et al 2023). Table 5 presents the results of groundwater suitability for irrigation on the basis of individual parameters and calculated analytical parameters including SAR, %Na, KR and RSC. Areas falling under different classes of groundwater fitness have also been tabulated.

Table 5. Area under different classes of groundwater quality for irrigation purpose (Adimalla & Qian, 2019).

Sr. No.	Parameters	Standard Values (WHO 2011; Zakir-Hassan et al 2023)	Suitable		Marginal		Unsuitable	
			Area (km ²)	%	Area (km ²)	%	Area (km ²)	%
1	Ec	1000	254.9	17	951.6	83	-	-
2	TDS	1000	35.6	2	1368.4	90	117.5	8
3	Na	200	2.6	0	1451.2	95	67.7	4
4	K	200	436.7	29	910.3	60	136.6	9
5	Ca	75	694.4	46	827.8	54	-	-
6	Mg	30	637.5	42	695.0	46	189.0	12
7	SO ₄	200	1324.9	87	2.9	0	193.7	13
8	NO ₃	50	815.8	54	693.3	46		0
9	Cl	250	651.1	43	719.4	47	150.9	10
10	Alk	10	894.5	59	573.2	38	55.9	4
11	SAR	<10	1522	100	-	-	-	-
12	RSC	<2.5	826	54	697.0	46	-	-
13	%Na	50	826.3	54	697.2	46	-	-
14	Kelly Ratio	>1	1354.9	89	155.5	10	4.5	1

Results of different individual parameters have been plotted to examine the spatial trends/patterns within the study area as. Figure 7 depicts some of geo-spatial distribution of Ca, Na,

K, Mg, TDS and Alk, while the Figure 8 shows the patterns for KR, %Na, SAR, and hardness in the study region.

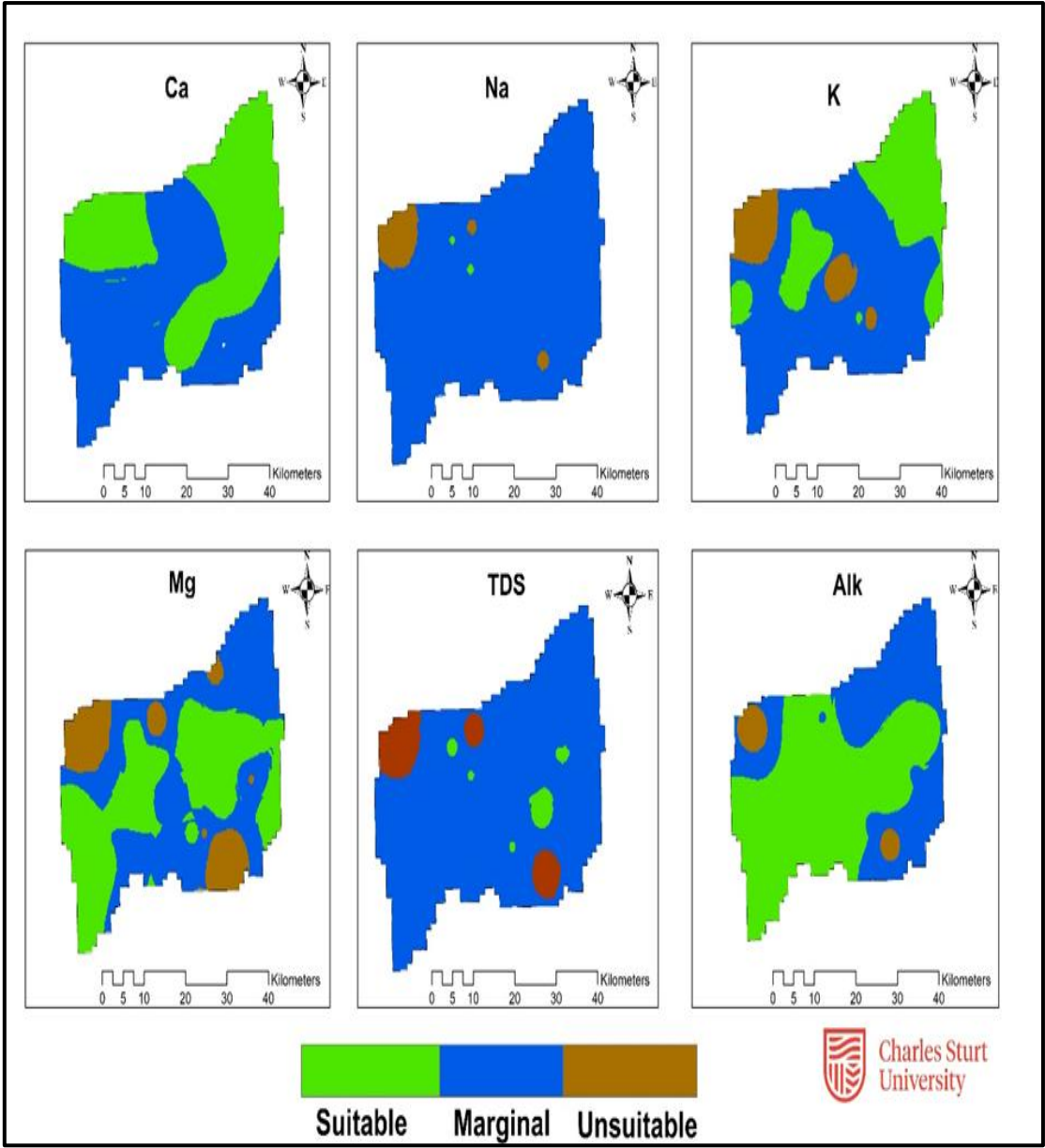


Figure 7. Geo-spatial distribution of analytical parameters ground water samples for irrigation use using IDW.

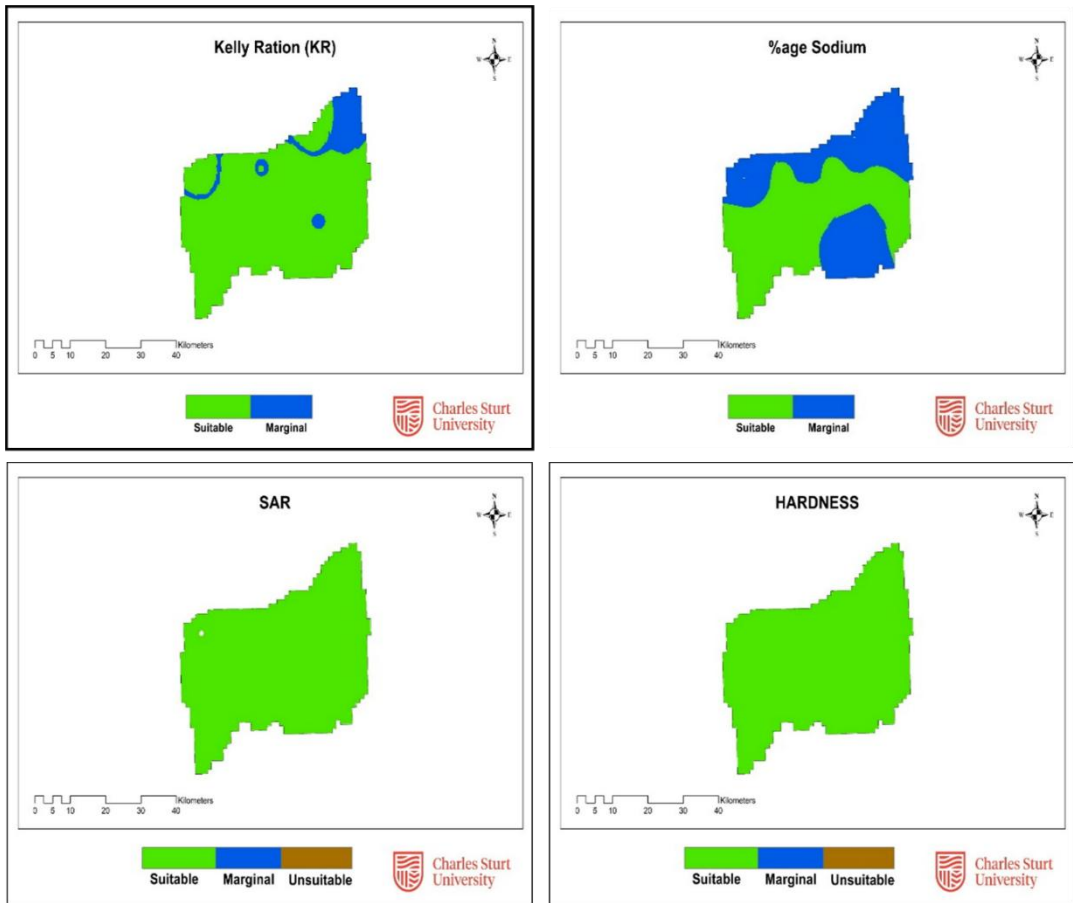


Figure 8. Geo-spatial of KR, %Na, SAR, hardness for groundwater samples for irrigation use by applying IDW.

Geospatial patterns (Fig 7) indicate that groundwater quality is generally suitable or marginal for irrigation application in the study area, however, there are some hotspots in the surrounding areas of Vehari city, which reflects that urban center is a source for groundwater contamination. Some other scattered locations also indicate the hotspots for groundwater quality near SBD and Ludden (a well-populated rural center of around 20000 persons). A small percentage of area up to 12% of the catchment contains water unsuitable for irrigation according to TDS, Na, K, Mg, SO₄, C; or Alk (Table 5 & Fig 7).

It is noted that most of the area is either suitable or marginal for irrigation uses (Fig 8) on the basis of SAR, Hardness, %Na, and KR values. The significant value is shown in SAR in which 100 % of area lies in suitable class. Other parameters also indicate that groundwater is generally suitable for irrigation. Figure 9 represents similar results for suitability of groundwater for irrigation on the basis of analytical parameters; which indicates that most the groundwater falls under the suitable and the marginal class. This too derives the findings that generally groundwater in the study area is suitable for irrigation.

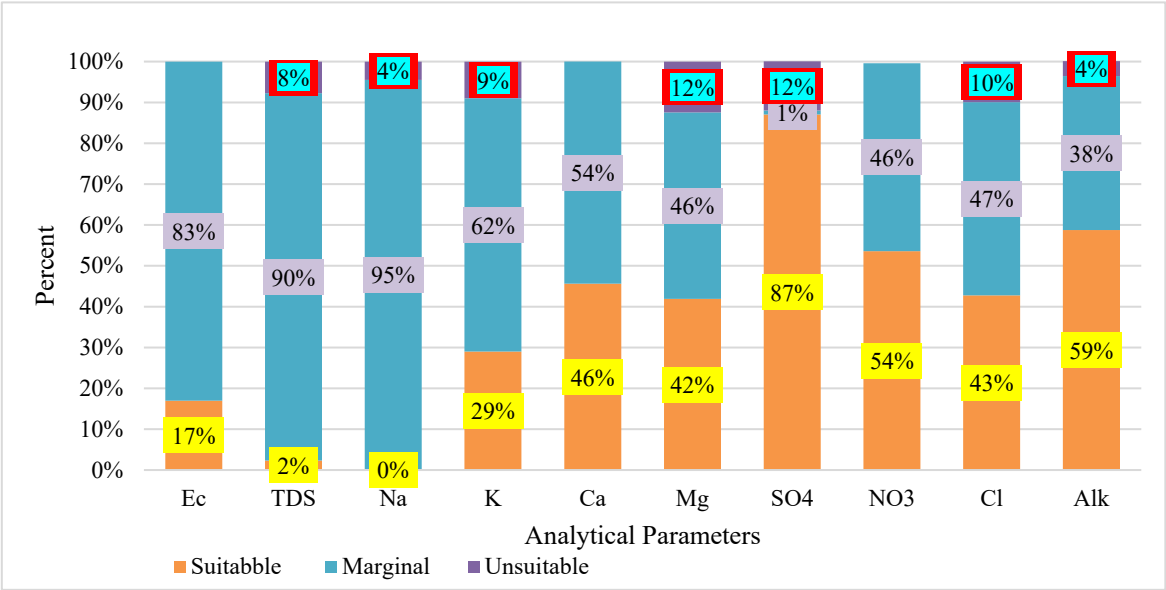


Figure 9. Suitability of groundwater on the basis analytical parameters for irrigation.

Additionally, some integrated parameters have also been calculated and plotted (Table 5, Fig 8) for evaluation and interpretation of groundwater quality for irrigation uses in the study area, which include %Na, KR, SAR, and RSC as shown in Figure 10. These parameters use the different individual elements and depict the overall picture of water quality for irrigation. These plots have revealed that groundwater quality in most of the part in the study area is suitable, and some patches fall under marginal categories. This also confers that groundwater in the aquifer is generally suitable for irrigation application except few spots near Vehari city, Ludden (an urban locality), and the SBD which passes through the study area.

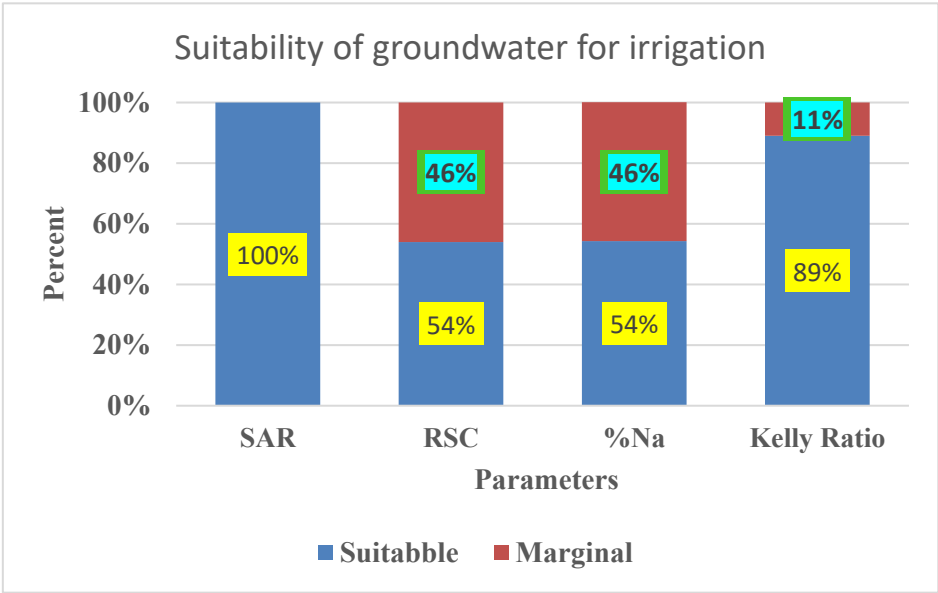


Figure 10. Suitability of groundwater for irrigation on the basis of integrated parameters (SAR, RSC, %Na, KR).

Due to high value of SAR (excessive Na), the soil becomes hard and compact when dry and resultantly, reduces the infiltration rates of water and air into the soil affecting its structure (Munkholm, 2011). This results in low recharge rates in the soils with high values of SAR (Hopkins et al., 2007). This problem is also related with several other factors such as the salinity rate and type

of soil. For example, sandy soils may not get damaged as easily as other type of soils (such as clay) when it is irrigated with a high SAR water (Zakir-Hassan, 2023).

It has been found that the dominant salt in groundwater in study area is Na, whose presence beyond permissible limits can pose the adverse impact when groundwater is used for irrigation. Uses of Na-excessive groundwater for irrigation purpose will cause accumulation of more salts (Na dominant) in the soil which affects the hydraulic conductivity (permeability) of soil and creates water infiltration problems. This is because when more Na is present in the soil in exchangeable form, it replaces Ca and Mg, adsorbed on the soil clays and makes the soil hard and cloddy when it is dry. While Ca and Mg cause dispersion of soil particles; i.e., if Ca and Mg cations are adsorbed on the soil exchange complex, the soil structure tends to improve as these cations stabilize soil aggregates, resulting in permeable and granular structure. This ultimately makes the soil more conducive to cultivation (Hopkins et al., 2007). Therefore, it is important to study what is composition of salts in groundwater and how salt and water interact with each other in root zone during irrigation. Excessive accumulation of Na is termed as soil sodicity which causes the degradation soil structure especially in clayey and loamy soils (van der Zee et al., 2014). Soil sodicity reduces the infiltration rates and increases the runoff causing the soil erosion (Wiesman, 2009).

The average groundwater quality was compared with surface waters sampled from drain, river and canal in the study area water samples as shown in Figure 11.

As shown if Figure 11, the EC values for drain water are the highest followed by in groundwater. It indicates that drain passing through the study area is the source of pollution for groundwater. Order of quality of different water is River > Canal > Groundwater > drain water. Similarly, BOD and COD for canal, river, and drain water have also been compared (Figure 12). Comparison of drain, river and canal water yielded the order of River > Canal > Drain. This implies that drainage water quality is the worst among all including groundwater, which warns about the contamination of land and water by drainage effluents.

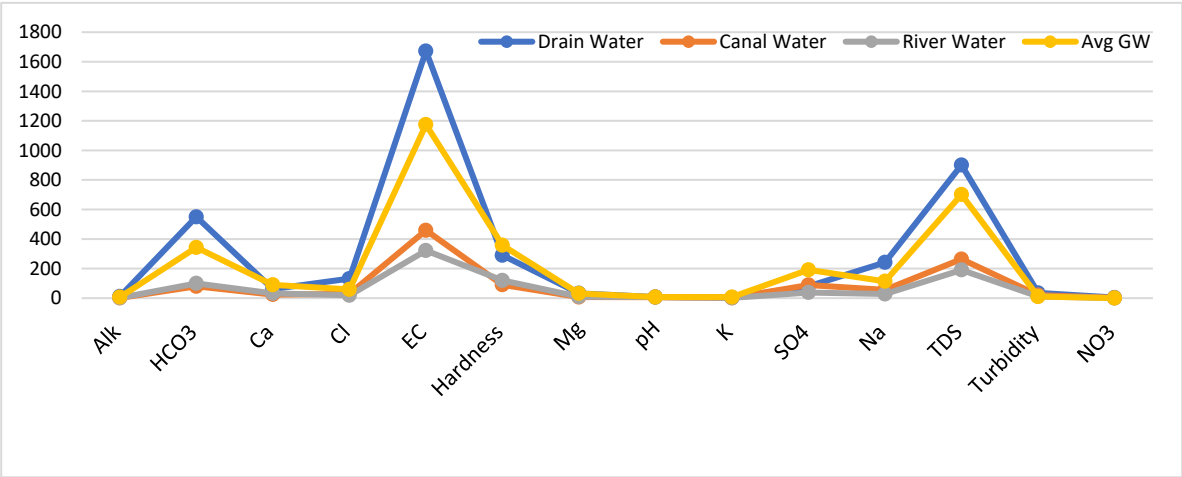


Figure 11. Comparison of average value of the groundwater with canal, river and drain waters samples.

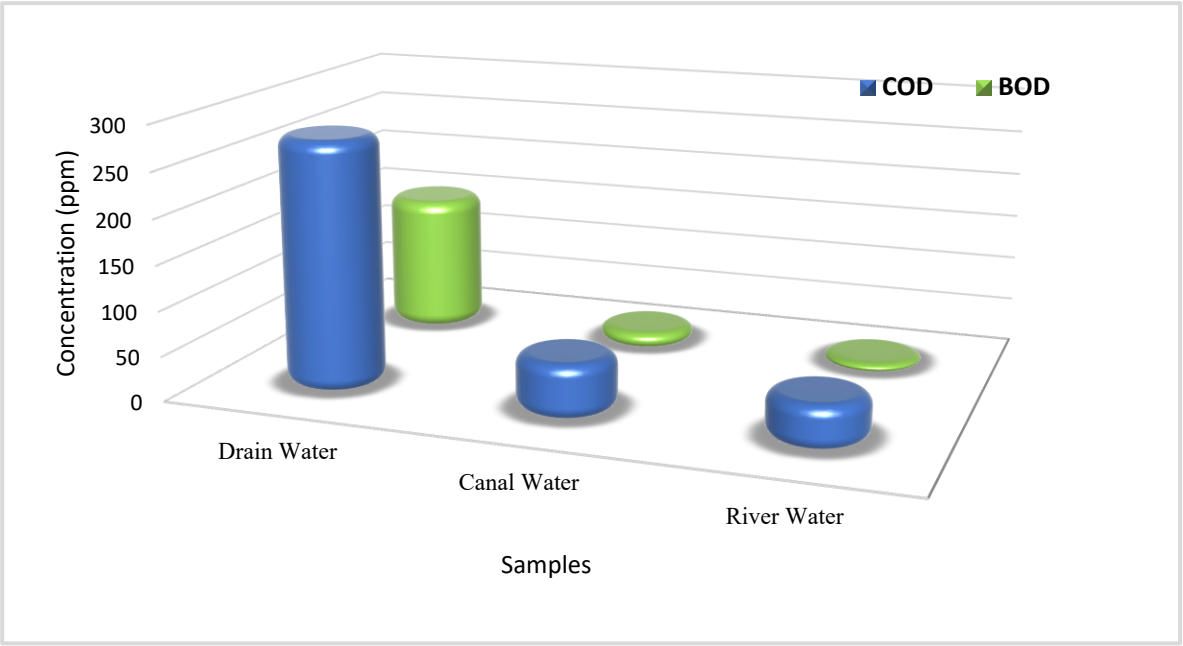


Figure 12. Comparison of BOD and COD of drain, river and canal water samples.

4. Conclusions and Recommendations

This research prescribes a benchmark survey and investigation on groundwater water quality situation in the study area which is important for the MAR project, which is being implemented by PID to improve the depleting groundwater levels. After implementation of MAR project, the quality of groundwater in the area can be re-assessed to evaluate the impact of MAR. This can help in future implementation of MAR projects in similar areas in IRB and other regions.

Groundwater quality has been compared with the available water for MAR (river water), which has been found better. Through this finding, it can be anticipated that MAR project of PID can improve the quality of groundwater in the study area. However, aviod the excessive use of groundwater for irrigation must be avoided as it may cause the problem of sodification in soil which may hamper the infiltrartion rates posing adverse impacts on MAR project. Farming community may be advised for suitable mangement interventions for groundwater quality includng conjunctive use, application of chemical like gypsum.

In addition, the study provides the extent of suitability of groundwater for irrigation purposes and domestic uses. Results have revealed that groundwater in the study area is generally suitable for irrigation but unfit for drinking. Regular direct use of groundwater may pose adverse effects on human health. Therefore, groundwater may be used for human consumption after filtration or other treatment to avoid the threatsto the community’s well being.

Groundwater quality for irrigation use is although generally suitable, but hotspots are there near urban centers and the Sukh Beas Drain, which indicates that domestic effluents from the urban centers are putting negative influence on the groundwater. Treatment of any type of effluent must be made mandatory to mitigate the threats for land and water resources in the area.

Findings of the study can be helpful in decision making regarding designing and implementation MAR projcets and planing for groundwater management including protection of aquifer in the area for sustainable and integrated water resources planning. Planning for protection of groundwater quality must be ensured.

For any MAR project the water quality of both source and sink play a vital role and must be evaluated and anticipated well before implementation of the projects on the ground. If source water is contaminated it may pollute the aquifer and, similarly, recharging the contaminated aquifers will be futile exercise. In addition to this aspect, another important dimension of water quality threats for MAR are the anticipated reaction of recharged water with the porous media through which the water

flows through during the recharge process (Zakir-Hassan et al 2023). Geological material of the aquifer also plays a significant role in the resultant water quality after implementation of MAR projects.

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