EQA - International Journal of Environmental Quality
ISSN 2281-4485 - Vol. 68 (2025): 37 - 49
Journal homepage: https://eqa.unibo.it/

published by

Spatiotemporal zoning of groundwater quality in Rechna Doab: analysis of Electrical Conductivity (EC), Sodium Adsorption Ratio (SAR), and Residual Sodium Carbonate (RSC) variability

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Article info
Received 21/1/2025; received in revised form 18/2/2025; accepted 26/2/2025
DOI: 10.6092/issn.2281-4485/21146

Abstract
Groundwater quality is essential for sustaining human and plant life, as its degradation can harm vital organisms critical for ecosystem balance. GIS-based models have proven effective in large-scale water quality zoning, offering precise and efficient management tools. Therefore, present study was designed with objective of water quality zoning in Rechna doab. This study analyzed borehole data from 1,130 wells across the Rechna Doab region, collected from 2006 to 2019 during pre-monsoon (June) and post-monsoon (October) seasons. Key water quality parameters, including electrical conductivity (EC), sodium adsorption ratio (SAR), and residual sodium carbonate (RSC), were interpolated using the inverse distance weighted (IDW) method in GIS. The results revealed that during the pre-monsoon season, 7.94% of the area exhibited poor water quality, 58.90% marginal, and 33.16% good quality. In the post-monsoon season, these values shifted to 11.65% poor, 52.43% marginal, and 35.93% good quality zones. Geo-statistical validation using semi-variogram and kriging demonstrated high model accuracy, with mean error (ME) and mean square error (MSE) values near zero. Additionally, root mean square error (RMSE) closely matched average standard error (ASE), though root mean square standardized error (RMSSE) values greater than 1 indicated overestimation for EC, SAR, and RSC. The study concluded that groundwater quality in Rechna Doab is deteriorating over time and recommends adopting artificial groundwater recharge and conservation strategies to preserve water quality.

Keywords: *water quality, interpolation, inverse distance weighted, geo-statistical, GIS, pre-monsoon, post-monsoon.*

Introduction

Water plays a vital role in the hydrological cycle, supporting environmental stability through processes like vaporization, precipitation, evaporation, evapotranspiration, and surface and subsurface runoff. As a fundamental element of the environment, it is essential for sustaining all forms of life (Ismail & Ahmed, 2021). Groundwater, the second-largest irrigation source after surface water, is declining due to overuse and excessive pumping. In recent decades, its contamination has become a global concern, threatening human health and environmental sustainability (Hudak, 2000; Tiwari et al., 2017). Similarly, surface water quality has deteriorated due to pollution from industrial waste, seawater intrusion, and fertilizer runoff, further threatening water resources (Sadat-Noori et al., 2014). The study of principal component analysis (PCA) method to relocate physico-chemical water quality of data sets and Multidimensional Positioning (MDS) method which describes interaction of

DOI: 10.6092/issn.2281-4485/21146

physic-chemical parameters between them and their influence on groundwater quality. It revealed strong correlation between water quality parameters like electrical conductivity (EC), total dissolved salts (TDS), sodium adsorption ratio (SAR), and residual sodium carbonate (RSC) and the presence of magnesium (Mg), calcium (Ca), cation exchange capacity (CEC), and sulfate (SO_4) ions, resulting in increased salinity deposits over time (Houria et al., 2020). GIS based DRASTIC models have also been used to delineate vulnerability of groundwater quality maps in Pakistan and concluded that higher values of EC and SAR could be harmful to crop production and irrigation water with poor quality may accumulate excessive salts in the root zone of soil (Shakoor et al., 2020). In Khartoum, during estimation of salinity effect on crop yield, it was observed that agricultural yields are suffering due to the use of poor quality saline water. The study found that for every unit increase in salinity, there was a significant loss in crop yield, with losses of 71.52, 35.24, and 21.84 kg/ha/ds/m recorded. These losses are extremely high and can have a detrimental effect on overall crop productivity. After analyzing water quality of samples collected from field area to analyze the effect of EC, SAR and RSC in the laboratory of Bahawalpur, it was observed that 50% of the water samples were unfit for irrigation. Bahawalpur is a major city for cotton and wheat crops, and it was estimated that the use of poor-quality saline with higher EC values, water would result in significant crop yield losses. To mitigate this issue, it is recommended to treat the water with gypsum salts before irrigation and to adopt the cultivation of saline-resistant crops in the region (Riaz et al., 2018). The study analyzed the effect of water quality on maize crop yield by measuring various parameters. The results showed that the plant height, seed germination rate, and grain size of the maize crop were adversely affected by the presence of saline water (Abbas et al., 2017). To improve water quality and increase crop productivity, the authors recommended the adoption of drip irrigation with the use of liquid fertilizers to maintain safe levels of water quality (Irfan et al., 2014). GIS-based models through interpolation of water quality parameters can also be used as a reliable tool to evaluate the overall water quality in a particular area. In addition, the use of remote sensing technology has also been beneficial in assessing groundwater quality by identifying land use changes and potential sources of contamination. Groundwater modeling is another important approach for assessing the effects of different parameters on groundwater quality and quantity. It can be used to simulate and predict groundwater flow, as well as to estimate the impact of land use change, climate change, and water management strategies on groundwater resources. By using these methodologies, it becomes easier to identify the sources of contamination, predict the movement of contaminants, and take appropriate measures to prevent or minimize contamination (Shakoor et al., 2020). In addition, these methods can also be used to evaluate the effectiveness of management practices and policies aimed at protecting groundwater resources. Therefore, the application of these methodologies is crucial for the sustainable management and conservation of groundwater resources, which is essential for ensuring the availability of clean and safe water for present and

Materials and Methods

Study Area

The Rechna doab region was chosen to study groundwater quality between 2006 and 2019. This area is situated between the Ravi and Chenab rivers, encompassing several major districts in Punjab province, including Gujranwala, Narowal, Hafizabad, Sheikhupura, Faisalabad, Nankana Sahib, Chiniot, Jhang, and Toba Tek Singh. The location of the study area is illustrated in Figure 1, and it is located between 30° 35' and 32° 50' N, and 71° 50' and 75° 3'E. The region is evenly distributed between the boundaries of the Ravi and Chenab rivers. The estimated total area of the Rechna Doab region is 28,500 km², with a surface elevation ranging from 180 to 238 meters, as determined by processing the Digital Elevation Model in GIS. The area is largely fertile and suitable for agricultural production, with a significant portion being utilized for this purpose. Surface and groundwater are the primary sources of water for the population, with groundwater being over-exploited during periods of high cropping intensity when water demand exceeds supply. The mean annual rainfall in the Rechna Doab region from 1980 to 2020 ranged from 200 to 778 mm. Due to the significant variation in rainfall between the rainy and non-rainy seasons, the area is classified as Pre-Monsoon and Post-Monsoon. During the pre-monsoon season, rainfall is typically low, while the post-monsoon season receives the majority of the rainfall. The climate in the study area is characterized by large fluctuations in seasonal temperature. The summer season (April to October) is considerably hotter than the winter season (November to March), with temperatures ranging from 21-51°C. The Rechna

DOI: 10.6092/issn.2281-4485/21146

Doab region is a well-irrigated area bounded by the Ravi and Chenab rivers, with fertile land that is ideal for agricultural production. The primary canal system serving the area is the Lower Chenab Canal (LLC), which originates from the Khanki headworks in the Gujranwala district. The LLC is further divided into two regions: LCC East and LCC West, with branch canals such as Rakh, Jhang, and Gugera supplying canal water throughout the Rechna Doab (Shakoor et al., 2020). The soil in the Rechna Doab region is characterized by a wide variation in texture and can be classified as fine (sandy clay, silt clay, and clay), medium fine (loam, silt loam, and silt), moderately coarse (fine sand, sandy loam), and coarse (sand, sandy loam). The soil is primarily composed of alluvial deposits that were transportted by the Indus River and its tributaries. The topography of the area is relatively flat, with uniform distribution from north to northeast.

Sampling Design

The study used a comprehensive sampling strategy to ensure spatial and temporal coverage across the Rechna Doab region. Water samples were collected from nine districts: Narowal, Sialkot, Gujranwala, Sheikhupura, Nankana, Hafizabad, Faisalabad, Jhang and Toba Tek Singh during two seasons, pre-monsoon and post-monsoon in one year. Well water samples were collected from 1,130 wells during the pre-monsoon (June) and post-monsoon (October) seasons from 2006 to 2019 to analyze the variation in chemical parameters such as electrical conductivity (EC), sodium adsorption ratio (SAR) and residual sodium carbonate (RSC) chemical parameters. Sampling locations were selected to represent diverse land uses, geological conditions and varying aquifer depths. Sampling intervals were also designed to capture annual and seasonal variations in groundwater quality. Consistency in sampling methods and equipment was maintained across all years to ensure data comparability.

Description of chemical analyses of water samples

The collected water samples were analyzed for key water quality parameters such as Electrical Conductivity (EC), Sodium Adsorption Rate (SAR) and Residual Sodium Carbonate (RSC). Each water sample was chemically analyzed to assess EC, SAR and RSC values. The chemical analysis was performed in certi-

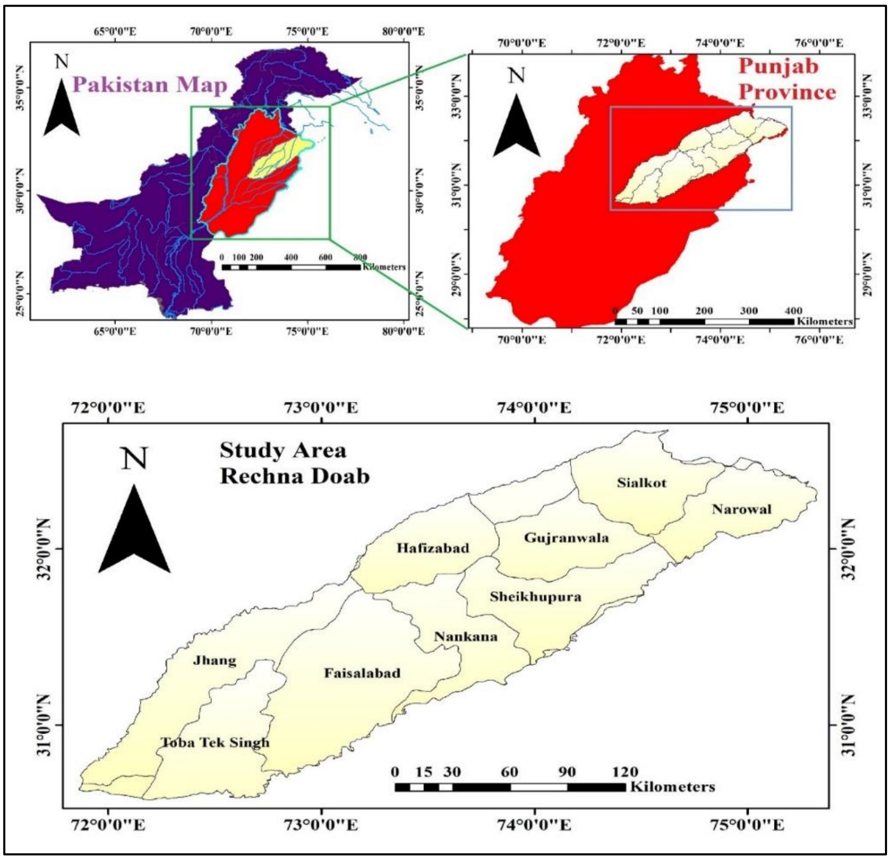

Figure 1
Location map of the study area (Rechna doab) in Punjab province of Pakistan

DOI: 10.6092/issn.2281-4485/21146

Fied laboratories following the standard methods for water analysis as described by the American Public Health Association (APHA). Stringent quality control measures including field duplicates, blanks and calibration standards were applied to ensure accuracy and reliability of the data. The EC, SAR and RSC values of all 1,130 water samples were organized year-by-year (2006 to 2019) in an Excel sheet twice a year (pre-monsoon and post-monsoon).

Description of Groundwater quality parameters and data sets

Electrical Conductivity **(EC).** The deposition of soluble salts in water can be measured using the electrical conductivity (EC) method, which determines the conductance of electrical current in the water and is measured in units of ds/m The greater the concentration of soluble minerals, ions, and salts in the water, the higher the EC value will be, as these substances allow electrical current to conduct through the water and salt particles. High EC values can indicate chemical interactions that may negatively impact plant cells, leading to decreased growth efficiency and lower plant yields (Aslam et al., 2021).

Sodium Adsorption Ratio **(SAR).** The sodium adsorption ratio is a measure of the concentration of sodium, calcium, and magnesium in water. It is defined as the ratio of sodium ions to the combined concentration of calcium and magnesium ions and is typically expressed as SAR units. The SAR value of water can be calculated using the following equation.

$$SAR = \frac{Na^{+}}{\sqrt{Ca^{2+} + Mg^{2+}}} \quad [1]$$

The concentrations of sodium, calcium, and magnesium in water are typically measured in milliequivalents per liter (meq/L). When water with a high SAR value is used for irrigation, the soil surface can become compacted and have poor drainage capacity. This can make it difficult for water to be available to plants and can cause an increase in intolerant soluble salts that can negatively impact crop growth. Therefore, it's important to monitor SAR values and use appropriate irrigation management techniques to prevent soil compaction and maintain healthy crop growth (Lesch & Suarez, 2009).

Residual Sodium Carbonates **(RSC).** The addition of alkaline hazardous materials and salts such as carbonates, bicarbonates, calcium, and magnesium to water molecules is referred to as residual sodium carbonates (RSC). The value of RSC is primarily determined by the concentration of sodium and magnesium lime materials in the water body. When RSC values exceed a certain threshold, it can negatively impact soil structure and reduce water infiltration, making it difficult for plants to access water and nutrients. Therefore, it's important to monitor RSC levels and take appropriate measures to mitigate their effects on soil and plant health.

$$RSC = (CO3^{2-} + HCO3^{-}) - (Ca^{+} + Mg^{+}) \quad [2]$$

It is measured in meq/L, and all elements have the same unit of concentration in water, greater RSC values will affect to decrease crop growth (Zaman et al., 2018). Data on groundwater quality, including EC, SAR, and RSC, was collected from the Punjab Irrigation Department for two seasons: pre-Monsoon and post-Monsoon. The data was segregated bore-wise and covered the entire region of Rechna Doab.

Criteria for water quality determination

The collected data on EC, SAR, and RSC were categorized into good, marginal, and poor-quality zones based on WHO standards. The aim was to map the water quality areas of Rechna doab district-wise by segregating the datasets into these three categories.

Development of EC, SAR & RSC layers

In remote sensing and GIS, IDW is used to interpolate the data to generate continuous surfaces for mapping and analysis purposes. Geo-statistical analysis involves modeling and analyzing spatially correlated data. It uses statistical methods to estimate and interpolate values at non sampled locations based on the spatial correlation of the sample data. Kriging is one of the most widely used geo-statistical techniques for the in-

DOI: 10.6092/issn.2281-4485/21146

interpolation of data, which predicts the values at non sampled locations by considering the spatial correlation of the observed data. The inverse distance weighted (IDW) method is a commonly used interpolation method for creating maps of environmental data. However, it should be noted that IDW assumes that the samples are evenly distributed throughout the area of interest and that the underlying spatial pattern is isotropic, which may not always be the case in practice. Geo-statistical analysis, on the other hand, is a more sophisticated approach that considers the spatial correlation between data points and the anisotropy of the underlying spatial pattern. This allows for a more accurate estimation of values at non sampled locations and a better understanding of the spatial structure of the data. Kriging is a popular geo-statistical method that uses a mathematical model to estimate values at non sampled locations based on the correlation between nearby samples. It considers the spatial autocorrelation of the data and allows for the creation of maps with varying degrees of spatial resolution and uncer-tainty. Initially, the maps of EC, SAR, and RSC were made using the ordinary kriging method through interpolation. Kriging is a popular geo-statistical method used for spatial interpolation particularly in remote sensing and GIS. It uses a set of observed values at known locations to estimate the values at unknown locations by minimizing the estimation error variance. This method takes into account the spatial correlation among data points and produces a smoother and more realistic surface than other interpolation methods like IDW(Webster & Oliver, 2007).

Multi-Criterial Overlay Analysis

Table 1 provides criteria for determining the groundwater quality categories of Good, Marginal, and Poor based on certain thresholds for EC, SAR, and RSC. These categories were then used to classify the interpolated values on the maps generated using the ordinary kriging method.

Parameters	Range	Quality	Re-class weightage
Electrical	<0.7	Good	3
Conductivity	0.8-3.0	Marginal	2
(EC) (ds/m)	>3.0	Poor	1
Sodium	<7	Good	3
Adsorption Ratio	~8-15	Marginal	2
(SAR)	>15	Poor	1
Residual	<1.25	Good	3
Sodium Carbonate	1.25-2.5	Marginal	2
(RSC)	>2.5	Poor	1
	08--9	Good	3
Overall	5--7	Marginal	2
	3--4	Poor	1

Table 1
Reclassification weight assigned to water quality parameters.

Geo-Statistical Analysis

Geo-statistical methods assume that the spatial distribution of the data is stationary, meaning that the statistical properties of the data do not vary across space. This is typically assessed through the calculation of a semi-variogram, which quantifies the degree of spatial autocorrelation in the data. Additionally, geo-statistical methods assume that the data is normally distributed, and may require transformation if it is not. Other techniques used in the geo-statistical analysis include cross-validation to evaluate the accuracy of predictions and trend analysis to account for non-stationarity (Abeed et al., 2019). It has three components: 1) Variogram or semi-variogram analysis involves analyzing the spatial autocorrelation of the data by calculating the variance of the differences between pairs of data points as a function of the distance or lag between them. 2) Kriging is a spatial interpolation method that uses the variogram/semi-variogram model to estimate the values of the variable at non sampled locations.

DOI: 10.6092/issn.2281-4485/21146

Kriging produces an unbiased estimate of the variable and an associated measure of uncertainty. 3) Stochastic simulation involves ge-nerating multiple equiprobable realizations of the spatial distribution of the variable, based on the vario-gram/semi-variogram model. These realizations can be used to assess uncertainty and explore different scenarios or management options (Bohling, 2005).

Cross-validation techniques

Cross-validation techniques are commonly used in geo-statistical analysis to assess the accuracy and reliability of the estimated results. These techniques involve comparing the predicted values with the actual measured values at different locations within the study area. These techniques are based on statistical analysis to recheck the accuracy of the estimated results of the semi-variogram models (Mohammadi et al., 2010). There are several parameters are available, but the following are the most used in research i.e., mean error (ME), root mean square error (RMSE), Mean Standardized Error (MSE), root mean square standard error (RMSSE), and average standard error (ASE).

Mean Error **(ME).** It measures the bias in the estimated values and is calculated as the average difference between the predicted values and the actual measured values (Seddiki & Dehimi, 2023). These parameters were described as Mean error (ME) was used to determine the degree of biases in estimated values and is calculated using Eq. (3), adopted from (Li et al., 2015).

$$\mathrm{ME} = \frac{1}{N}\sum_{i=1}^{N} [\bar{Z}(X_i) - Z(X_i)] \qquad [3]$$

Root Mean Square Error **(RMSE).** This parameter measures the closeness of the predicted values to the actual measured values. It is calculated as the square root of the average of the squared differences between the predicted values and the actual measured values. The RMSE represents the intimacy of the model results with measured groundwater quality values (Delgado et al., 2010). The lesser values of this error indicate better prediction.

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} [\bar{Z}(X_i) - Z(X_i)]^2} \qquad [4]$$

Mean Standardized Error **(MSE).** This parameter measures the relative error in the predicted values and is calculated as the average ratio of the difference between the predicted values and the actual measured values to the standard deviation of the actual measured values. Mean Standardized Error (MSE) is the average of the standardized errors and its value should be close to 0.

$$\mathrm{MSE} = \frac{\sum_{i=1}^{n} \left(\hat{Z}\left(s_i - z(s_i)\right)\hat{\delta}(s_i)\right)}{n} \qquad [5]$$

Root Mean Square Standardized Error **(RMSSE).** This parameter is similar to RMSE but takes into account the relative error in the predicted values. It is calculated as the square root of the average of the squared ratios of the difference between the predicted values and the actual measured values to the standard deviation of the actual measured values. The RMSSE describes the estimation variability. If its value is greater than 1, the model is underestimating the variability in predictions. If its value is less than 1, there are chances of overestimating the variability in predictions (Esri, 2011).

$$\mathrm{RMSSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} \left[\left(\bar{Z}(X_i) - \frac{Z(X_i)}{\sigma^*}\right)(X_i)\right]^2} \qquad [6]$$

The abbreviations used in these equations are, n is the number of groundwater observations, Z is the value of observed groundwater quality Z is the value of predicted groundwater quality and σ^{*2} (Xi) is the Kriging variance for location Xi.

The Average Standard Error **(ASE).** This parameter measures the overall accuracy of the estimated values and is calculated as the average of the absolute differences between the predicted values and the actual measured values. Average Standard Error (ASE) is the average of the prediction standard errors.

$$\mathrm{ASE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} \sigma^{*2}(X_i)} \qquad [7]$$

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Results and Discussion

This section discusses the spatial and seasonal variations of key groundwater quality parameters i.e., Electrical Conductivity (EC), Sodium Adsorption Ratio (SAR), and Residual Sodium Carbonate (RSC), and their combined effect on the overall groundwater quality in the Rechna Doab region. The results are presented for both the pre-monsoon and post-monsoon seasons, with emphasis on regional differences and the potential causes of water quality changes.

Electrical Conductivity **(EC).** The spatial distribution of EC during the pre-monsoon season revealed distinct variations across the Rechna Doab region. The northern areas (e.g., Narowal) exhibited good water quality with low EC values, indicating minimal salt content. In contrast, central areas (e.g., Gujranwala, Hafizabad, Sheikhupura, and Faisalabad) showed marginal EC levels, while southern regions (e.g., Jhang and Toba Tek Singh) experienced poor water quality due to high salinity. Post-monsoon improvements in EC were observed, with good water quality zones expanding in Sialkot, Narowal, and Gujranwala districts. The increased precipitation during the monsoon likely contributed to salt leaching and dilution of saline groundwater, reducing overall salinity levels (Bouaroudj et al., 2019; Ilić et al., 2019). Spatial variation of Electrical Conductivity (EC) during pre-monsoon and post-monsoon seasons have been represented in Figure 2. The observed trends in EC are primarily influenced by agricultural practices and irrigation with saline wa-ter. In southern districts, long-term irrigation without proper drainage likely led to salt accumulation in the soil, exacerbating salinity issues. Similar patterns have been reported in regions such as southern India and the Sahara Desert, where continuous use of saline wa-ter has degraded soil profiles and groundwater quality (Brindha & Kavitha, 2015; Pimentel et al., 2004). Ba-sed on observed trends in EC, recommendations for managing high EC include promoting the use of low-salinity irrigation water, implementing drainage sy-stems to prevent salt buildup, and adopting salt tolerant crop varieties.

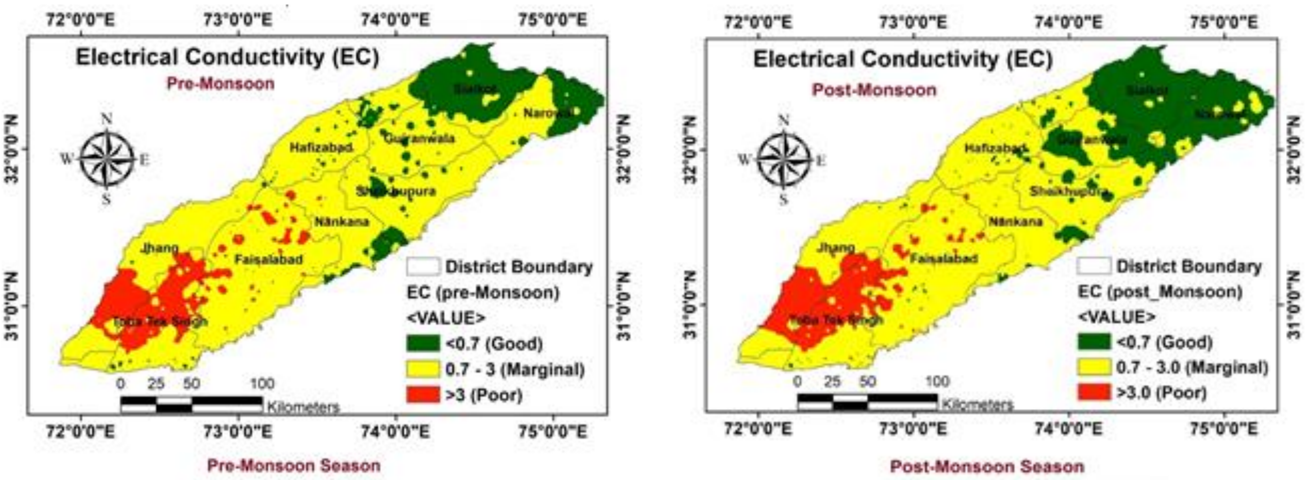

Figure 2. *Spatial interpolation of Electrical Conductivity (EC) for pre-monsoon and post-monsoon seasons*

Sodium Adsorption Ratio **(SAR).** In the pre-monsoon season, the spatial distribution of SAR has been represented in Figure 3 district-wise of Rechna doab, the upper region of doab showed good quality of SAR. The sodium adsorption ratio (SAR) is an index of the potential of a given irrigation water to induce sodic soil conditions. By excessive sodicity, the clay minerals in soils tend to swell and disperse and aggregates tend to slake, especially under conditions of low total salt concentration and high pH. As a re sult, the permeability of the soil is reduced, the surfa--ce becomes more crusted, and the infiltration rate of the soil decreases. Similarly, the spatial variation of SAR during post-monsoon has been shown in Figure 3, district-wise in Rechna doab. It could be observed that the post Monsoon season contains a larger area of good quality than the pre-monsoon season. Marg-inal quality of SAR was observed in some areas of Hafizabad, Nankana, and Jhang districts, while Toba Tek Singh and Faisalabad have major areas with poor SAR due to the presence of salts and lack of sewa-ge/industrial water treatment facilities.

DOI: 10.6092/issn.2281-4485/21146

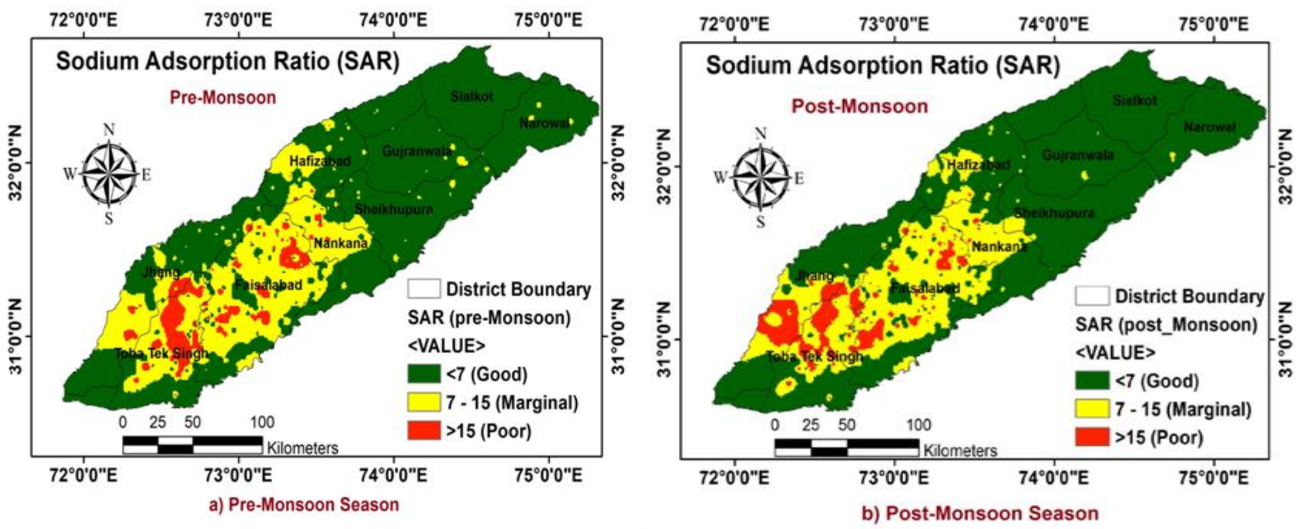

Figure 3. *Spatial interpolation of Sodium Adsorption Ratio (SAR) for pre-monsoon and post-monsoon seasons*

***Residual Sodium Carbonates* (RSC).** RSC plays a critical role in determining the suitability of irrigation water for agricultural purposes. High RSC levels indicate an excess of carbonates and bicarbonates, which can lead to calcium and magnesium precipitation and an increase in sodium concentration. This can significantly affect soil structure and permeability, reducing water infiltration and root zone effectiveness. During the pre-monsoon season, spatial analysis revealed widespread poor RSC values across the Rechna Doab region. Poor RSC was particularly prevalent in districts such as Sialkot, Gujranwala, Sheikhupura, Faisalabad, and Hafizabad, with some pockets of good RSC quality observed in Toba Tek Singh and Jhang districts. The accumulation of carbonates and bicarbonates during the dry pre-monsoon period is likely a result of prolonged irrigation with carbonate-rich water and insufficient leaching. High RSC values can also reduce soil permeability, leading to restricted water movement and compromised plant growth. Post-monsoon RSC values showed significant improvements across much of the Rechna Doab region. The reduction of high RSC values was most notable along the Ravi River bank in Sialkot and Faisalabad districts. The increased precipitation during the monsoon season likely facilitated natural leaching processes, allowing for the removal of excess carbonates and bicarbonates and improving the overall water quality. This phenome-non underscores the importance of rainfall in flushing out harmful salts and restoring soil health. Spatial variation of RSC in pre-monsoon and post monsoon season district-wise is represented in Figure 4.

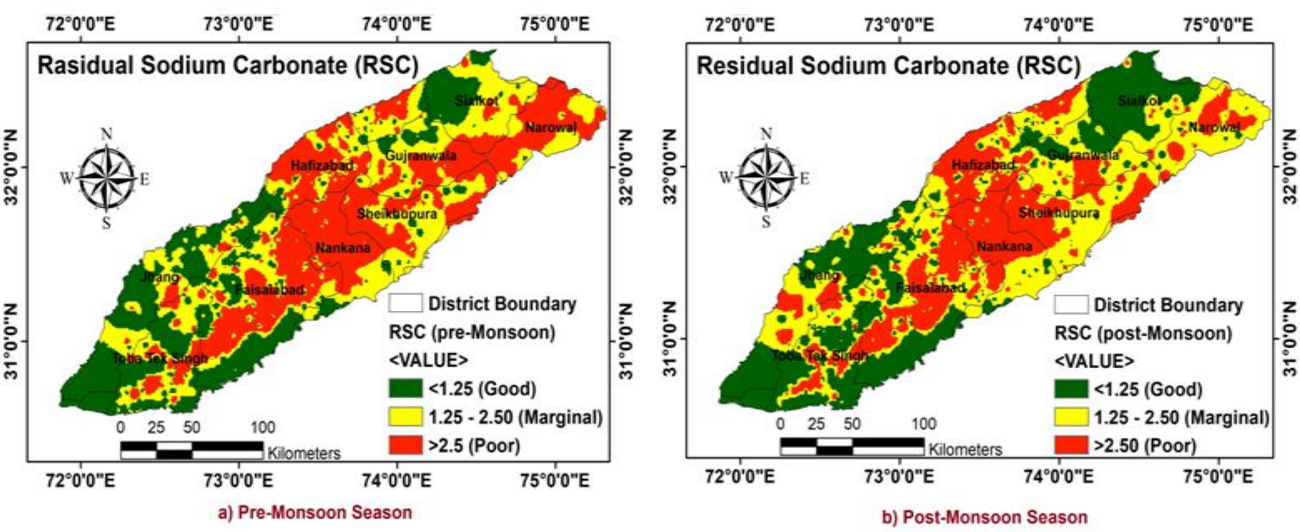

Figure 4. *Spatial interpolation of Residual Sodium Carbonate (RSC) for pre-monsoon and post-monsoon seasons*

DOI: 10.6092/issn.2281-4485/21146

The high RSC values in the pre-monsoon season are a major concern for agricultural sustainability, as they can lead to soil sodicity, crusting, and reduced infiltration rates. The improvements observed during the post-monsoon season highlight the positive impact of rainfall on groundwater quality. However, relying solely on natural rainfall is not sufficient to address long- term soil salinity and sodicity issues. The observed variations in RSC values across different seasons highlight the dynamic nature of groundwater quality in the Rechna Doab region. Sustainable water and soil management practices will be essential to preserving agricultural productivity and mitigating the adverse effects of high RSC levels.

A thematic layer of overall water quality

The spatial distribution of overall groundwater quality in Rechna Doab was derived using weighted overlay analysis of the key water quality parameters: Electrical Conductivity (EC), Sodium Adsorption Ratio (SAR), and Residual Sodium Carbonate (RSC). Each parameter was assigned a specific weight based on its relative influence on water quality to generate composite water quality layers. This classification resulted in three groundwater quality zones: poor, marginal, and good. During the pre-monsoon season, the spatial distribution of groundwater quality revealed distinct trends across the Rechna Doab region. Poor groundwater quality was observed in Nankana, Faisalabad, and Toba Tek Singh districts. These areas exhibited elevated levels of EC, SAR, and RSC, indicating increased salinity, sodicity, and bicarbonate concentrations in the water. The use of saline irrigation water and untreated effluent discharge are likely contributors to this deterioration. Over time, these conditions may reduce soil permeability and crop productivity. Marginal groundwater quality dominated much of the central portion of Rechna Doab, encompassing Gujranwala, Hafizabad, and Sheikhupura. These zones are vulnerable to further degradation due to continuous irrigation with marginal-quality water. Without adequate management, these areas may transition to poor quality zones in the future. Good water quality zones were primarily located in the northern districts of Sialkot and Jhang. These areas benefited from lower salinity and balanced sodium, calcium, and magnesium levels. The relatively better water quality in these zones may be attributed to higher rainfall, natural leaching, and limited saline water usage. The pre-monsoon season's overall pattern indicated that groundwater quality in the southern parts of the region was more vulnerable to salinity and sodicity, while the northern areas remained relatively stable. The post-monsoon season exhibited a noticeable improvement in groundwater quality across the region, A significant reduction in poor quality zones was observed, particularly in areas such as Sialkot, Gujranwala, Hafizabad, and Sheikhupura. The dilution effect of monsoon rainfall played a critical role in improving water quality by flushing out salts and lowering SAR and RSC levels. Additionally, natural leaching during heavy rainfall may have reduced bicarbonate accumulation in the soil profile. Some areas previously classified as poor transitioned to marginal quality zones. Although still vulnerable, these zones demonstrated partial recovery during the post-monsoon season. This highlights the importance of seasonal recharge and suggests that targeted management strategies could further enhance groundwater quality. The good quality zones expanded during the post-monsoon season, with areas in Sialkot, Jhang, and parts of Gujranwala and Hafizabad showing notable improvement. Increased groundwater recharge and reduced salinity stress were key factors contributing to this positive trend. The seasonal variability in groundwater quality underscores the importance of natural processes, such as monsoon rainfall, in regulating salinity, sodicity, and bicarbonate accumulation. The zoning analysis demonstrated clear spatial and seasonal trends in groundwater quality across the Rechna Doab region. While the post-monsoon season showed overall improvement, continued efforts in irrigation management, artificial recharge, and wastewater treatment are essential to prevent further groundwater quality deterioration. Sustainable water management practices will play a vital role in ensuring the long-term viability of the region’s water resources. Overall combined water quality variation for both seasons has been shown in figure 5. Similarly, overall water quality zones were extracted by using weighted overlay analysis of EC, SAR, and RSC water quality layers, divided into poor, marginal, and good subset values, and all layers were assigned with a weighted number to counterpart the combined effect of water parameter layers. It was observed that during the post-monsoon season, the water quality was observed to increase in safer zones which were in marginal or poor water quality zones already in the pre-monsoon season. It could be seen as the dominant effect of improvement in water quality in Sialkot, Gujranwala, Hafizabad, and Sheikhupura respectively. The zoning of water quality during the post-monsoon season is represented in Figure 5.

DOI: 10.6092/issn.2281-4485/21146

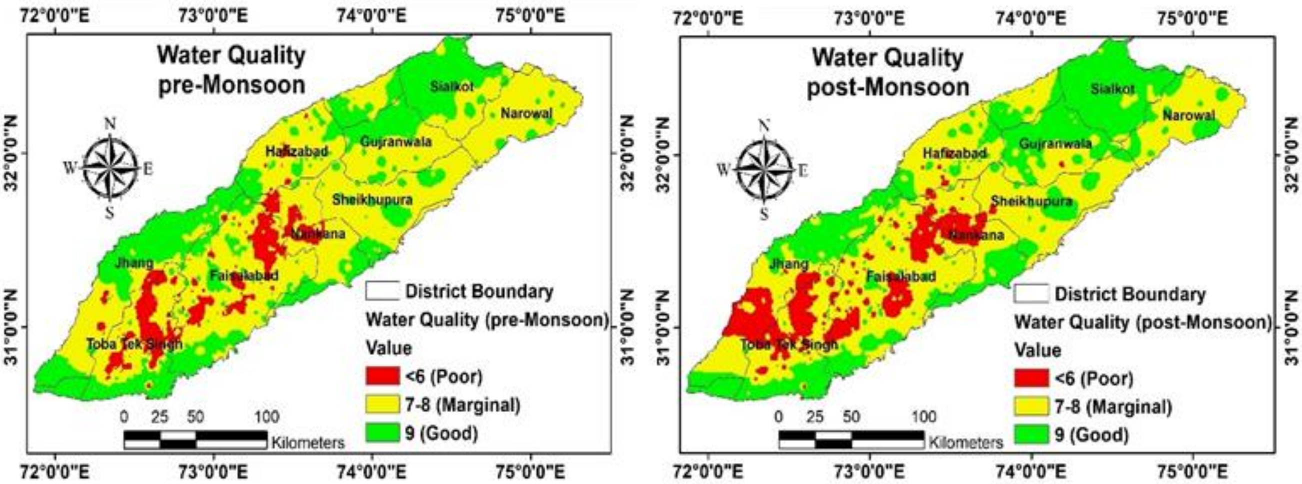

Figure 5. *Spatial distribution of combined water quality for pre-monsoon and post-monsoon seasons*

Interpretation of cross-validation of results

The geo-statistical model through GIS played a pivotal role to determine the kriging variance because it is equally necessary to be accurate for the determination of probability kriging. Probability kriging utilizes the semi-variogram (the mathematical model in GIS) which generates the additional information related to the developed model for the parameter (variable) concerning the original data of binary variable, it includes autocorrelation estimation for each parameter as well as its cross-correlation. Water quality parameters (EC, SAR, and RSC) were used to determine the effectiveness and validation of water quality model fitness with the cross-validation of statistical parameters i.e., mean error (ME), root mean square error (RMSE), average standard error (ASE), mean standard error (MSE), root mean square standard error (RMSE) for the pre-monsoon and post-monsoon seasons. The values determined for cross-validation parameters have been listed in Table 2.

Table 2
Cross-validation results of water quality parameters for pre-monsoon and post-monsoon seasons

Season	Parameter	ME	RMSE	MSE	RMSSE	ASE
Pre-Monsoon	EC	0.0006	1.1146	0.0003	1.0441	1.0721
	SAR	-0.0062	5.7595	-0.0011	0.9733	5.9275
	RSC	-0.0068	2.1770	-0.0021	0.9799	2.2255
Post-Monsoon	EC	-0.0004	1.0838	-0.0005	1.0362	1.0499
	SAR	-0.0072	5.9107	-0.0011	0.9915	5.9616
	RSC	0.0100	2.2035	0.0044	0.9776	2.2624

The best fitness of the model is lying on mean error (ME) and square mean error (MSE) values, if they are closer to zero and the model is considered accurate, when the values of root mean square error (RMSE) are much nearer to values of average standard error (ASE). moreover, a thumb role is followed to verify the best fitness of model by analyzing the root mean square standard error (RMSSE) values nearer to 1, if the values of parameter's RMSSE is greater than 1, then the model is termed as overestimated. If the values obtained are observed less than 1, the model is considered to be underestimation (Pham et al., 2018). ME values have been observed for pre-monsoon where the negative sign could be seen for pre-monsoon SAR and RSC. While for post-monsoon season EC and SAR values have been observed, the negative sign indicates the model simulated values are higher than the measured values.Geo-statistical investigation has helped to determine the water quality parameters (EC, SAR and RSC) in Rechna doab at district level and tendency of groundwater quality through temporal variation in Faisalabad and Toba Tek Singh, Jhang, Sialkot, Gujranwala, Hafizabad, Sheikhupura and Narowal districts of Punjab – Paki-

DOI: 10.6092/issn.2281-4485/21146

stan. It was determined that sodicity and salinity were major threats to groundwater quality due to excessive values of RSC and EC, and overall water quality was found marginal (50-55%) to poor (39-44%) at Faisalabad district (Khan et al., 2022). Groundwater quality has been found as marginal to unfit for drinking purpose using water quality index in Faisalabad district (Abbas et al., 2023). Similar results were observed for groundwater levels determination at Rechna doab, where it was concluded that groundwater level was found at decreasing trend due to excessive pumping of water (Abbas et al., 2023). Under this study, aim was to determine the groundwater quality of Rechna doab by analyzing water quality parameters, therefore zoning of water quality was done through spatial interpolation of EC, SAR, and RSC values district-wise in Rechna doab for pre-monsoon and post-monsoon seasons over the period of 2006-2019. The degree of deterioration of water quality was determined by accessing the EC, SAR, and RSC parameter values year wise, cumulatively 1130 bore well data was used in interpolation and generated the groundwater quality of EC (0.7-12.23), SAR (0-27) and RSC (0.2-8.50) for pre-monsoon and post-monsoon seasons. Variation between seasonal analyses was observed in EC on average pre-monsoon and its 2.77% area was increased to a good water quality zone during the post-monsoon season. Similarly, SAR and RSC at the district level were observed to be improved during post-monsoon season. Three thematic layers EC, SAR, and RSC were spatially imported into weighted overlay analysis, where suitable numbers were assigned through 1-3 based on the effect of water quality parameter, for example, in the EC map, three ranges were shown <0.7 (good), 0.7-3 (marginal) and greater than 3 (poor), good water quality was ranked at 1 and 2 for marginal and poor quality with 3 number. Similarly, weighted rank values were assigned to SAR and RSC parameters and combined water quality was determined through interpolation in weighted overlay analysis for pre-monsoon and post-monsoon seasons respectively. Zoning was spatially distributed at the district level for both seasons, which determined the poor, marginal, and good water quality zones. The resulting maps were spatially validated through geo-statistical analysis which used ordinary kriging and semi-variogram. Measure and predicted graphs normalized and error value graphs and modeled and binned graphs for EC, SAR, and RSC values were drawn for both seasons (pre-monsoon and post-monsoon). The effectiveness and validation of water quality model fitness with the cross-validation of statistical parameters i.e., mean error (ME), root mean square error (RMSE), average standard error (ASE), mean standard error (MSE), root mean square standard error (RMSE) for the pre-monsoon and post-monsoon seasons were determined to develop the relationship between measured and predicted results. It was estimated that EC, SAR, and RSC mean error (ME) were found nearer to zero. The values of root mean square error (RMSE) was found much nearer to values of average standard error (ASE). The values of parameter's RMSSE is greater than 1 for EC, SAR, and RSC for both seasons. Therefore, the models were termed as overestimated and none values obtainned as underestimated. Cross-validation provided the authentication of measured values with predicted values and a geo-statistical investigation was observed as a precise, accurate, and fast method that generated groundwater quality parameters (EC, SAR, and RSC) in terms of poor, marginal, and good quality zones in Rechna doab.

Conclusions

This study employed GIS, geo-statistical analysis, and map overlay techniques to evaluate groundwater quality in Rechna Doab, Punjab, Pakistan, focusing on electrical conductivity (EC), sodium adsorption ratio (SAR), and residual sodium carbonate (RSC). Data from 1,130 borewells collected during pre-monsoon and post-monsoon seasons (2006–2019) were analyzed to assess spatial and temporal variations. with notable improvements in SAR and RSC. Weighted overlay analysis classified EC into three ranges: <0.7 (good), 0.7–3 (marginal), and >3 (poor), with corresponding rankings of 1, 2, and 3, respectively.

- Pre-monsoon results showed 7.94% poor, 58.90% marginal, and 33.16% good zones.
- Post-monsoon results indicated 11.65% poor, 52.43% marginal, and 35.93% good zones.
- Pre-monsoon values ranged from EC (0.7–12.23 dS/m), SAR (0–27 mmol/L½), and RSC (0.2–8.50 meq/L).
- Post-monsoon values were EC (0.3–14 dS/m), SAR (0.1–24 mmol/L½), and RSC (0.2–9.8 meq/L).
- A 2.77% increase in good-quality water zones was observed post-monsoon due to recharging groundwater.

Geo-statistical validation using semi-variogram and kriging methods yielded mean error (ME) and mean square error (MSE) values near zero, confirming mo-

DOI: 10.6092/issn.2281-4485/21146

del accuracy. Root mean square error (RMSE) closely aligned with average standard error (ASE), though root mean square standardized error (RMSSE) values exceeding 1 for EC, SAR, and RSC indicated model overestimation. Cross-validation results for EC, SAR, and RSC during both seasons are presented in Table 2, highlighting the spatial distribution of declining water quality in Rechna Doab.

Acknowledgments
Research work is part of the Ph.D. thesis the author, it was carried out to determine potential groundwater zones for recharging sites to improve groundwater quality and quantity. All the authors are thankful to the Punjab Irrigation Department for providing the water level and quality data for validation.

Author contributions
The first author (M Abbas) conceived the idea, designed the study, collected information from various sources, standardized the datasets, drafted the work, and revised it critically for important intellectual content. The second (M Arshad) and third author (A Shahid) reviewed the manuscript and completed the article for publication.

Funding
No specific funding has been received to conduct this piece of research.

Data availability
All the utilized data sources of this research are very clearly written under Sect. 2.2 of the article.

Declarations Conflict of interest
We would like to declare that we have no known competing fiscal interests or personal relationships that could have appeared to influence the work reported in this paper.

Consent for publication
This paper has not yet been published and is not currently being considered for publication. If accepted, it will not be published anywhere in the same manner, in English or any other language, even electronically, without the copyright holder's express agreement.

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