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Integrated Assessment and Geostatistical Evaluation of Groundwater Quality through Water Quality Indices

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Abstract: This study undertook an assessment of 24 physiochemical parameters at over 1094 sites to compute the water quality index (WQI) across the upper and central Punjab regions of Pakistan. Prior to the WQI calculation, an analytical hierarchy process (AHP) was employed to assign specific weights to each water quality parameter. The categorization of WQI into distinct classes was achieved by constructing a pairwise matrix based on their relative importance utilizing Saaty's scale. Additionally, the groundwater quality status for irrigation and drinking purposes across various zones in the study area was delineated through the integration of WQI and geostatistical methodologies. The findings revealed discernible heavy metal issues in the Lahore division, with emerging microbiological contamination across the entire study region, potentially attributed to untreated industrial effluent discharge and inadequately managed sewerage systems. The computed indices for the Lahore, Sargodha, and Rawalpindi divisions fell within the marginal to unfit categories, indicating water quality concerns. In contrast, the indices for other divisions were in the medium class, suggesting suitability for drinking purposes. Scenario analysis for developing mitigation strategies indicated that primary treatment before wastewater disposal could rehabilitate 9% of the study area, followed by secondary (35%) and tertiary (41%) treatments. Microbiological contamination (27%) emerged as the predominant challenge for water supply agencies. Given the current trajectory of water quality deterioration, access to potable water is poised to become a significant public concern. Consequently, government agencies are urged to implement appropriate measures to enhance overall groundwater quality for sustainable development.

Keywords: analytical hierarchy process (AHP); ground water quality; water pollutants; GIS; landuse landcover

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1. Introduction

Water exists as two primary sources, i.e., groundwater and surface water. Out of the present 2.5% of the earth's freshwater resources, 30% reflects groundwater [1]. However, anthropogenic activities combined with natural factors frequently cause groundwater quality to deteriorate. Nevertheless, the key drivers of groundwater quality degradation are recognized as industrialization, population growth, and inadequate waste management practices [2]. Pakistan is the fourth largest groundwater consumer in the world, and more than half of the country's overall crop water requirements are met by this finite source [3].

According to the National Bureau of Statistics of Pakistan, nearly half of the population has access to safe water, while only 26.1% satisfy international drinking water standards [4]. Punjab is the most populated province of Pakistan. The population of Punjab increased from 20 million in 1951 to more than 110 million in 2017 [5]. Rapid urbanization, industrialization, unplanned consumption of groundwater, and lifestyle changes are increasing water demand [6]. Furthermore, about 90% of the Punjab household population relies on groundwater reserves for daily water demands.

Water quality is one of the most critical challenges in managing water resources [7]. The unconfined aquifers of the Punjab province are gradually contaminated through leaks from the sewerage system, dumping of untreated effluents, and leachate from landfill sites. The unconfined alluvial aquifers in the study area are increasingly threatened by contamination from untreated municipal and industrial wastewater discharges, leachate infiltration, and agricultural runoff containing fertilizers and pesticides. A review of the Punjab region highlighted the rapid urban expansion, industrialization, and population pressures as key factors underlying water pollution risks to vulnerable aquifer zones tapped for irrigation and potable use [8]. Recent modeling studies have shown elevated groundwater nitrate levels in rural Punjab districts, indicating the impacts of fertilizer application for intensive cropping patterns [9]. Moreover, abstractions from the aquifer are rising at a rapid rate to meet the ever-increasing water demands due to reduced surface water availability [10]. The WQI serves as an indicator of the waterbody's condition [11] and is commonly employed to encapsulate the intricate interplay of factors influencing water quality, encompassing a diverse array of parametric measures [12]. Indeed, establishing WQI is an essential step in water resource management and has gained worldwide importance as a tool for measuring the water quality of aquatic bodies. Various multicriteria decision-making techniques have been applied to evaluate the effects of different alternatives on water. For example, ref. [13] employed the WQI to evaluate water quality in distinct stages, employing two multicriteria decision-making (MCDM) methods: (1) AHP and (2) assessing attractiveness using a categorically based evaluation methodology. Drinking water quality and suitability for potable use are major concerns for the region's groundwater reserves, which are tapped extensively to meet municipal demands.

Sutadian et al. [14] highlighted the significance of the precise determination of weights for different water quality indicators in formulating the WQI. Previous studies have employed various methods to calculate the weights for water quality indicators; for instance, ref. [15] stated that the AHP method has the capability to manage all sorts of water resources based on social, economic, and environmental criteria. In addition, the efficacy of the indicator weights calculation process may be increased by combining the AHP with other procedures. Reference [16] stated that the AHP method is the most reliable tool for assigning the ranks as it is based on the universally accepted Saaty's scale. Moreover, it indicated that the AHP method is a better choice in determining the relative importance of objectives, sub-objectives, and alternatives in selecting the best irrigation methods. Refs. [17,18] employed GIS and MCDA to generate the groundwater quality index in which the AHP was utilized to determine the weights of numerous criteria and their classes.

Ref. [19] utilized the National Sanitation Foundation Water Quality Index (NSFWQI) in an environment suitable for irrigation. Researchers globally have applied the water quality index to assess groundwater quality in various regions, such as Dier al-Balah, Palestine. Ref. [20], Sereflikochisar Basin of Turkey [21], Telangana State, South India [22], the Coastal Zones of Srikakulam, India, ref. [23], Iraqi city of Karbala [24], Iran's Lenjanat plain aquifer ([25], Ranchi, Jharkhand, India [26].

Previous studies on groundwater quality assessment in Pakistan have investigated a limited set of parameters, mostly focused on major cities, including Lahore [27], Rawalpindi and Islamabad [28], Lower Jhelum Canal [29], and the industrialized city of Faisalabad [30] using the integrated geospatial and water quality index approaches in Pakistan. While providing important insights into groundwater pollution sources in urban areas, the water quality evaluations have been constrained to a few heavy metals and microbiological parameters. A comprehensive analysis incorporating a broader range of quality indicators across rural and urban areas at the provincial scale has been lacking.

This study aims to address this gap by evaluating the groundwater quality status in Punjab province through an integrated modeling approach utilizing a more expansive set of 24 physicochemical and microbiological parameters. The parameters were measured at over 1094 sampling sites across five divisions—Lahore, Rawalpindi, Sargodha, Faisalabad, and Gujranwala—encompassing both rural and urban areas. The larger spatial scale spanning the entire populous Punjab region provides new insights into groundwater pollution patterns across hydrogeological zones and land use categories.

The integrated water quality indexing and geospatial techniques applied to the extensive provincial water quality dataset also represent a novel contribution to delineating groundwater quality zones and identifying priority areas for mitigation strategies. The study develops an AHP-based weighted water quality index considering the suitability of drinking and irrigation usage. The indexed groundwater quality layers are then analyzed in conjunction with land use, depth to water table, groundwater recharge, and other factors to holistically characterize the key drivers of groundwater pollution at the Punjab scale. Moreover, different management scenarios were developed by altering the current wastewater treatment methods and evaluating the impact of various water quality indicators on WQI to improve groundwater quality.

2. Methodology

2.1. Study Area

The study area, Punjab province, situated in the semiarid lowlands zone, is the most populous province of Pakistan, with a population exceeding 110 million. The study area is comprised of an alluvial plain structured by the Indus River, with its major tributaries flowing into the southern part. The main rivers, i.e., River Ravi and River Sutlej, mostly recharged the groundwater aquifer. The soil composition of the Punjab plains is predominantly alluvial deposits originating from the Indus River system. The province has a semiarid, subtropical climate with mean annual minimum and maximum temperatures of 18.2 °C and 31.9 °C, respectively. It is characterized by chilly winters and hot summers. Rainfall distribution in the study region is uneven, with the monsoon season contributing 50–75% of the total rainfall, primarily influenced by monsoon winds. Groundwater is a major contributor to meeting water supply demands. From 1976 to 2012, the irrigation dependency on groundwater doubled as most of the groundwater withdrawals for irrigation purposes occurred in Punjab, in the canal command areas, with 70% of private tube wells and others being dependent on groundwater-based irrigation.

Key industries relevant to groundwater pollution include textiles, tanneries, pulp and paper, fertilizer, metal smelting, and automobile manufacturing clustered around urban centers. The unconfined alluvial aquifers of central and upper Punjab, which are tapped heavily for irrigation and domestic usage, are thus under constant risk of contamination from urban, industrial, and agricultural sources. Pakistan's major cities mainly rely on groundwater for their domestic purposes, as 70% of the drinking water for the total population of the country has been sourced from groundwater. The ever-increasing domestic and agricultural water demands due to urbanization and population growth have put constant pressure on the groundwater reserves, resulting in over-abstraction. This situation causes water levels to decline and negatively affects groundwater quality for any purpose [31]. Hence, conducting a comprehensive study is imperative to evaluate the groundwater quality for both drinking and irrigation purposes, as shown in Figure 1.

2.2. Overall Research Framework

The foundational research framework for this study is illustrated in Figure 2. A comprehensive dataset of 1094 groundwater samples was gathered from monitoring wells spread across the Punjab province study area. These sites were strategically located within the five divisions of Lahore, Rawalpindi, Sargodha, Faisalabad, and Gujranwala. Physicochemical parameters such as pH, chloride (Cl^-), fluoride (F^-), iron (Fe^-), nitrate (NO_3), nitrite (NO_2), arsenic (As), total hardness, bicarbonate (HCO^{3-}), calcium (Ca^{+2}), magnesium

(Mg^{+2}), color, taste, turbidity, and total dissolved solids (TDS), along with microbiological parameters including total coliforms, fecal coliforms, and Escherichia coli, and irrigation parameters such as electrical conductivity (EC), residual sodium carbonates (RSC), and sodium adsorption ratio (SAR), were sourced from the Water and Sanitation Agency (WASA), Urban Unit Department, and Punjab Irrigation Department. Additionally, data on depth to the water table and precipitation were collected and incorporated into the water quality index (WQI) calculations. Furthermore, satellite imagery from Sentinel-2A MSI (multispectral instrument) captured in 2018 was obtained from USGS, interpreted, and used to identify land use through supervised classification. The unconfined alluvial aquifers in the study area are part of an interconnected groundwater system underlying the fertile Punjab plains. As discussed in [32,33], these aquifers are primarily composed of Quaternary alluvium comprised of alternating layers of sand, silt, and clay recharged by the region's canal network and major river tributaries. Groundwater also occurs under semi-confined conditions in some zones within Tertiary and Cretaceous sedimentary formations below the shallow alluvial deposits.

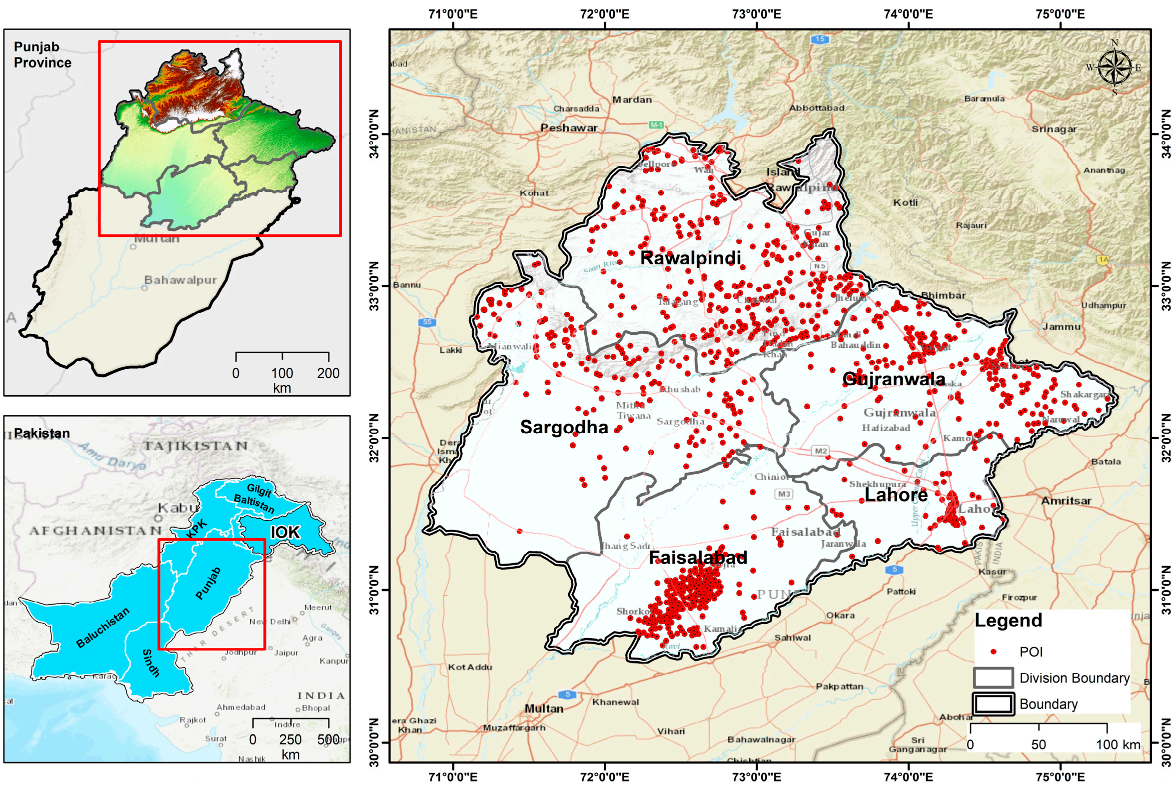

Figure 1. Study area map.

The calculation of the groundwater quality index involved a systematic four-step process: (1) parameter selection, (2) transformation into sub-indices, (3) determination of weights, and (4) aggregation of sub-indices to derive the final index value. The analytical hierarchy process (AHP) was employed to establish weights for the selected parameters. In the AHP methodology, pairwise comparisons of water quality parameters were fundamental. Priorities for the primary criteria (i.e., drinking and irrigation) were set side by side in a pairwise matrix, determined by their relative importance using the Saaty scale. The resulting index was categorized into distinct classes. Following the computation of indices for drinking and irrigation purposes, these values were interpolated to delineate various zones within the study area. Identification of quality zones facilitated the proposition of diverse management strategies aimed at ameliorating groundwater quality and sustaining overall groundwater conditions for developmental sustainability, as shown in Figure 2. The foundational research framework for this study is illustrated in Figure 2. A comprehensive dataset of 1094 groundwater samples was gathered from monitoring wells spread across the Punjab province study area. These sites were strategically located within the five divisions of Lahore, Rawalpindi, Sargodha, Faisalabad, and Gujranwala.

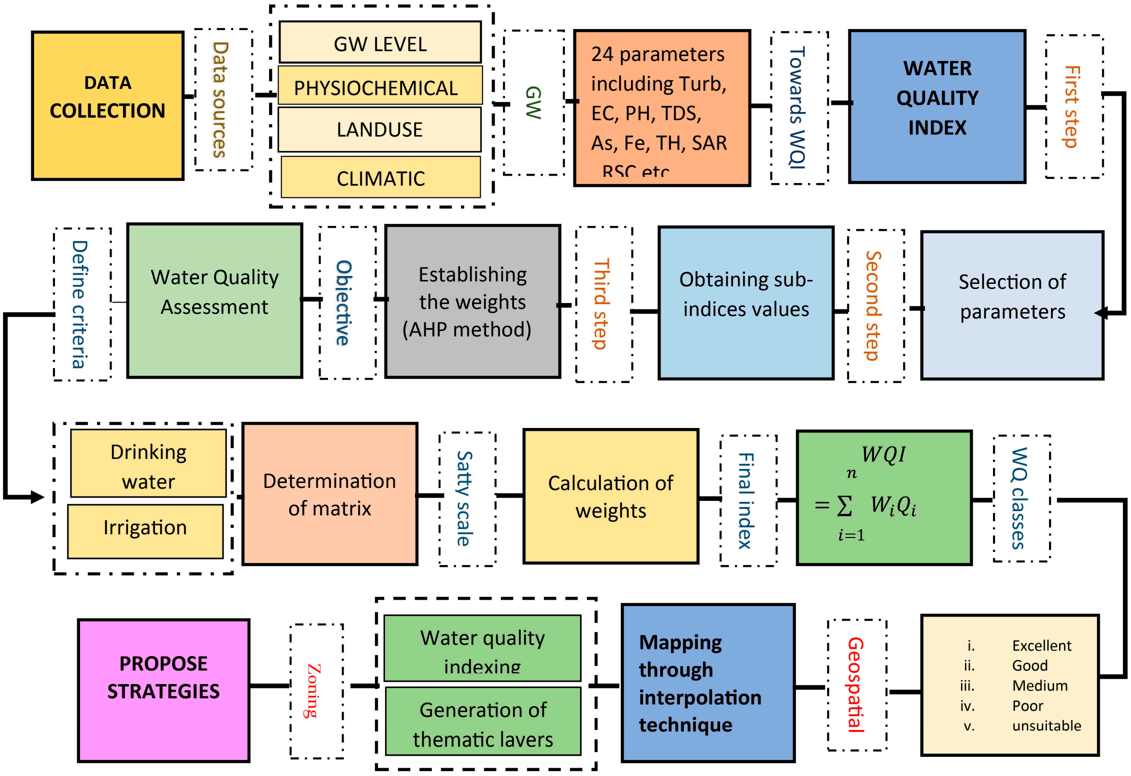

Figure 2. Methodological research framework.

2.3. Water Quality Index (WQI)

The fundamental necessity for the WQI development lies in the precise definition of the qualitative status of groundwater resources within the study area. This aspect is deemed crucial in the effective management and regulation of groundwater for diverse purposes [34]. The WQI reflects the status of the groundwater environment at any time and assists in developing management strategies for sustainable development. Indeed, establishing the WQI is an important step in groundwater resources management and has grown in importance as a tool for analyzing water quality all over the world. A water quality index is a unitless numerical representation that consolidates a chosen set of parameters into a singular measure, providing an indication of the overall quality of a water body.

The present study incorporates the various physical, chemical, heavy metals, and microbiological parameters in the computation of the groundwater quality index. Although all WQIs have a similar overall structure, the development of an index had two primary goals. These aims can range from broad water quality assessments to specific applications. Many indices were devised following Horton's [35], but despite these efforts, a widely accepted way of producing water quality indices has yet to be developed. The four typical phases used to compute the WQI have been discussed in the subsequent section.

Spatial interpolation techniques were applied in ArcGIS 10.6 to create continuous surfaces of the groundwater quality index layers for drinking and irrigation suitability. The IDW interpolation method was employed, relying on the recorded index values. The IDW calculates cell values by applying a linearly weighted blend of a designated set of sample points, where the weight is determined by the inverse distance. The geostatistical analyst extension was utilized for processing the resulting surface. The risk maps were classified into zones representing groundwater quality suitability levels for drinking and irrigation uses. Additionally, the LULC map was developed from Sentinel-2 satellite imagery. The images were preprocessed and atmospherically corrected, and the NDVI index was derived using ArcGIS. A supervised classification was performed to categorize the land use classes.

2.3.1. Selection of the Parameters

For calculating the index, selecting the water quality parameters is the primary and most important step. The parameters (i.e., physical, chemical, microbiological, and heavy metals) that greatly influence the groundwater quality are selected and shown in the Figure 3. The groundwater quality parameters were selected based on the review of the literature [36], data available [37], and parameter redundancy [38] to reflect the overall status of water quality.

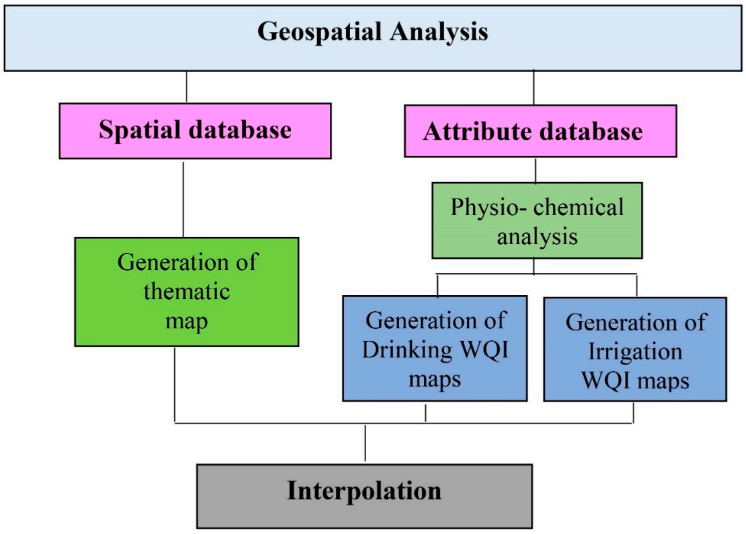

Figure 3. Geospatial analysis of the WQI.

2.3.2. Transformation to Sub-Indices

The parameters possess distinct units, and this phase involves transforming the water quality parameters into a standardized scale. For example, ammonia nitrogen is measured in mg/L, but turbidity is measured in NTU. Most WQIs can only be aggregated when the parameters have the same standard scales. Hence, normalizing to establish sub-indices is obligatory. The selected parameters (indicators) are classified into positive and negative indicators. Positive indicators are higher and better, and negative ones worsen the water quality [39]. The ideal situation comprises higher positive indicators and smaller negative indicator values.

The parameters are normalized using the following equations.

For the positive indicators,

$$R_i = \frac{x_i - x_{\min}}{x_{\max} - x_{\min}} \tag{1}$$

For the negative indicators,

$$R_i = 1 - \frac{x_i - x_{\min}}{x_{\max} - x_{\min}} \tag{2}$$

Here, Ri denotes the sub-index of the study region I, xi is the actual value of the indicator in region I, while x_{min} and x_{max} represent the minimum and maximum values in the dataset, respectively.

2.3.3. Determination of the Weights

Different weights were assigned to selected parameters based on their relative importance, and their impact on the final index value was assessed. The assigned weights can either be equal or vary. In cases where all index parameters are considered equally important, weights are assigned equally. However, if certain parameters are deemed more significant than others, varying weights are applied. This study employed the analytical hierarchy process (AHP) to calculate and assign weights to different parameters.

2.3.4. Expert Survey Limitations

While the AHP methodology using expert input provides a robust framework for assigning criteria weights, some biases may have inadvertently influenced responses. Academic experts may have fixated more on heavy metals and toxins due to their research priorities, while water management practitioners are inclined towards indicators of operational relevance. The specific backgrounds of experts can skew perceptions of parameter importance based on narrow specializations. Additionally, the sample size of 25 experts limits broad representativeness. Expanding and diversifying the expert panel in future assessments could help mitigate potential biases and restrictions in the current findings. Standard statistical tests should also be applied to ascertain the level of randomness and reliability of responses. Addressing these biases and sampling limitations would enhance the objectivity of criteria weighting outputs.

2.4. Analytical Hierarchy Process (AHP)

The AHP is a robust and valuable tool for addressing the qualitative and quantitative multicriteria aspects inherent in decision-making. This method adopts a subjective approach, assigning weights through pairwise comparisons between various criteria, as guided by policies proposed by [40]. The hierarchical process commences with establishing a goal derived from the research objectives concerning water quality assessment. This is contingent upon the criterion or criteria, such as drinking and irrigation, followed by the identification of alternatives, encompassing physical, chemical, heavy metals, and microbiological parameters. The AHP unfolds in three stages: parameter selection, subsequent construction of pairwise comparisons, and calculation of the corresponding weights.

For generating a pairwise matrix, the researcher must establish the priorities for the main criteria (drinking, irrigation) by setting them side by side on their relative importance. The structured questionnaire was crafted employing the widely recognized Saaty scale, utilizing a scale ranging from 1 to 9 points to assess the relative importance of parameters in relation to each other. The Saaty scale provides a standardized methodology for eliciting expert judgments on the importance of criteria through pairwise comparisons, allowing priorities and weights to be derived mathematically. This scale is highly recommended for its universal acceptance, offering a comprehensive range of options to discern the relative importance among parameters.

For each query, indicate the response that most accurately reflects your perception of the importance of water-quality parameters for drinking purposes. Utilize the 1–9-point scale for the comparative analysis shown in Table 1 [41].

Table 1. The 1–9 point scale used for the pairwise comparisons.

Scale	Relative Importance	Scale	Relative Importance
1	Equally important	1	Equally important
3	Moderately important	1/3	Moderately less important
5	Strongly important	1/5	Weakly important
7	Very strongly important	1/7	Very weekly important
9	Extremely important	1/9	Extremely important
2, 4, 6, 8	Intermediate values	1	Equally important

The AHP questionnaire was distributed to 25 experts consisting of 15 university professors from the departments of environmental science, geology, and hydrogeology and 10 water management professionals from government agencies. This sample of respondents was selected to provide perspectives from both academic and practical water quality management domains. The experts had an average of 12 years of experience related to groundwater research or management in the region. By incorporating input from both scientific experts and water practitioners, the aim was to derive balanced criteria weights that reflect technical groundwater quality considerations as well as applied management needs.

Responses were transported matrices, and the relative importance of the parameters for two criteria, drinking and irrigation, were noted. These responses were computed to calculate the weights of individual parameters. All the respondents give more importance to the As, fecal coliforms, total coliforms, TDS, and Iron. In some exceptions, the researchers assigned more weights to nitrate, *E. coli*, and chloride. All other parameters were assigned relatively the same importance. The higher weights were assigned to the heavy metals since heavy metal contamination is increasing exponentially in urbanized areas.

2.4.1. Construction of Pairwise Matrix

Judgments made by the respondents were then transformed into numerical values. Here, we compared the different parameters as 'n,' the number of parameters in pairs according to the relative importance assigned by the respondents. Denote the parameters by '$P_1, P_2 \ldots P_N$' and their weights by $p_1, p_2 \ldots p_{N.}$ of matrix A [40]. The matrix's diagonal members are all uniformly set to one. As a result, as the equation below shows, the lower triangular values were automatically calculated from the upper triangular component of the matrix replies shown in Table 2.

$$\begin{bmatrix} 1 & p12 & \cdots & p1n & \\ p21 & 1 & \cdots & p2n & \\ \vdots & \vdots & \ddots & \vdots & = 1 \\ pn1 & pn2 & \cdots & 1 & \end{bmatrix} \tag{3}$$

Table 2. Selected indicators and AHP Weights.

Criteria	Alternatives	Standard Value	AHP Weight
Drinking	Taste		0.010
	Odor		0.010
	Color		0.010
	Turbidity	1 NTU	0.029
	pH	6.5–8.5	0.040
	TDS	1000 mg/L	0.057
	Total hardness	120–180 mg/L	0.050
	HCO_3	500 mg/L	0.053
	Ca	75 mg/L	0.049
	Mg	50 mg/L	0.046
	Cl	250 mg/L	0.041
	F	1.5 mg/L	0.045
	Iron	0.3 mg/L	0.052
	NO_3	50 mg/L	0.035
	NO_2	3 mg/L	0.039
	As	10 mg/L	0.147
	T. Coliform		0.073
	Fecal coliform		0.099
	E. coli		0.026
	Water levels		0.074
	Precipitation		0.015
Irrigation	SAR		0.258
	EC		0.570
	RSC		0.171

Weight calculation (by eigenvector)

The weights are generally elicited using matrix algebra to find the primary eigenvector $w = (w_1, w_2 \ldots w_N)$ from matrix P where $w_i > 0$.

$$\sum_{i=1}^{n} w_i = 1 \quad (4)$$

when a matrix is normalized, the primary eigenvector for $w_i = 1$ becomes a priority vector for that matrix (i.e., weights) (Saaty, 1980).

According to (Saaty, 1980), the primary eigenvector of P is the desired eigenvector. The following equation can be used to calculate the priority vector w.

$$Aw = \Delta_{Max}(w) \quad (5)$$

where Δ_{Max} is the matrix A's most significant eigenvalue, and w is the corresponding eigenvector.

The weights of individual parameters were estimated across all hierarchy levels using the eigenvalue method [42].

2.4.2. Calculation of the WQI

At this stage, the indices of various parameter groups underwent aggregation through mathematical procedures. These calculations produced a sub-index value based on the assigned weights to specific parameters, ultimately determining the overall water quality status. The aggregation process employed the additive method to establish the water quality index. The final index value was computed using the following equation [43].

$$WQI = \sum_{i=1}^{n} W_i Q_i \quad (6)$$

where n represents the number of parameters selected, W_i is the weightage of individual parameters, and Q_i depicts the measured value or experimental laboratory value of the parameters.

3. Results

3.1. Variations in the Water Quality Parameters

3.1.1. Physiochemical Parameters

pH

The pH indicates the concentration of hydrogen ions in logarithmic units. pH measurements were recorded in different divisions in the study area for the year, such as Lahore (7.6–8.7), Rawalpindi (7.5–8.3), Sargodha (7.8–8.5), Faisalabad (7.9–8.6), and Gujranwala (7.2–7.9), as depicted in Figure 4a. A slightly alkaline pH was observed in the Lahore division in the Sheikhupura district, which could be potentially attributed to the industrial activities in that area.

Turbidity

Turbidity is defined as the clarity of the water optically. Turbidity is mainly caused by suspended particles that can be organic or inorganic. The sources of the turbidity are the sediments (mostly clay soils), which are harmless, but if the hazardous contaminant gets attached to them, they will have adverse effects on the environment and health [44]. Turbidity is a deputy indicator of other physical properties in various fields, including wastewater management, water quality assessment (drinking, irrigation), planning, and ecological studies. According to WHO standards, water turbidity should not exceed 5 NTU. The study results reveal that turbidity in the study area ranged from 2 NTU to 9 NTU, with the highest values observed in Sargodha (6.9 NTU) and Rawalpindi (5.2 NTU), as illustrated in Figure 4b. This indicates a need for treatment in certain areas of the study, including a sedimentation process to remove water turbidity effectively.

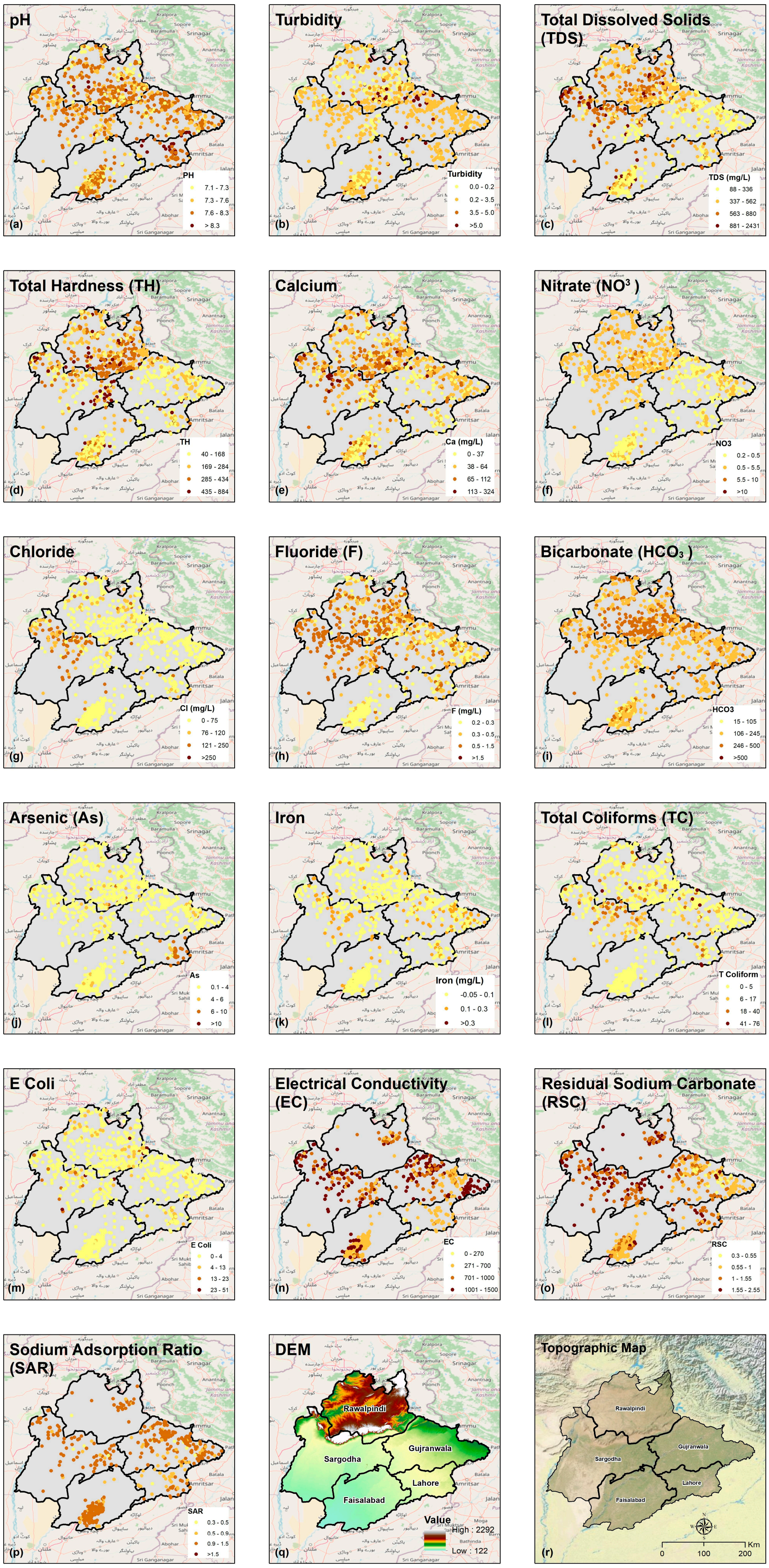

Figure 4. Spatial variations of the groundwater parameters. (**a**) pH (**b**) Turbidity (**c**) TDS (**d**) TH (**e**) Calcium (**f**) Nitrite (**g**) Chloride (**h**) Fluoride (**i**) Bicarbonate (**j**) Arsenic (**k**) Iron (**l**) TC (**m**) *E. Coli* (**n**) EC (**o**) RSC (**p**) SAR (**q**) DEM (**r**) Topographic map.

Total Dissolved Solids (TDS)

The total dissolved solids (TDS) indicate the soluble number of inorganic salts, generally representing the minerals present in the water. Elevated TDS levels not only impact water taste but also contribute to water hardness. The increase in TDS is attributed to various elements, including chloride (Cl^-), total hardness, bicarbonate ($HCO_3{}^-$), calcium (Ca^{+2}), and magnesium (Mg^{+2}). According to WHO standards, the TDS level in drinking water should not exceed 1000 mg/L. The findings indicate a TDS range of 75–1350 mg/L, with the highest values observed in the Sargodha (300–1350 mg/L) and Rawalpindi (104–1257 mg/L) areas. Some sections of Faisalabad and Lahore exceeded permissible limits, as depicted in Figure 4c, primarily due to rock–water interaction beneath the ground.

Total Hardness

Total hardness depends on the concentration of calcium (Ca^{+2}) and magnesium (Mg^{+2}). Water's hardness is not polluted when it is only due to the carbonates causing the temporary hardness. When combined with the bicarbonates, it leads to permanent hardness. Water with a high concentration of hardness is not suitable for drinking. Hardness in water causes pipe blockage and alteration in taste and even leads to various diseases, including cardiovascular disease [45]. For total hardness, the maximum number of samples higher than the standard value recorded in Sargodha ranges from 110 mg/L to 669 mg/L, as shown in Figure 4d.

Calcium

Calcium is the fifth most abundant element found in water. The major sources of calcium are gypsum and calcite found in sedimentary rocks [46]. The primary sources of calcium are rock–water interactions and contamination of industrial and domestic wastes [47]. The calcium ion serves as the primary contributor to water hardness, with concentrations ranging from 12 mg/L to 160 mg/L. Areas with elevated values include Sargodha (166 mg/L) and Rawalpindi (114 mg/L), as illustrated in Figure 4e. The WHO guidelines specify an acceptable limit of 75 mg/L for magnesium concentration in drinking water.

Nitrate

Nitrate for the environment is a less severe issue if present within the permissible limits, but if the nitrate concentration exceeds the limits, collaborating with other factors leads to eutrophication. The major sources of the contamination are the excessive use of nitrogen-based fertilizers, domestic effluents, and leakage of sewage systems [48]. The nitrate value should not exceed 10 mg/L, but in the study area, overall, 6% of samples exceeded the limits set by the WHO. The results show that the parameter ranges from 2 mg/L to 18 mg/L, as shown in Figure 4f.

Chloride

Chloride is naturally present in relatively small amounts in water. The elevated chloride concentration results from industrial and sewage effluent contamination, leachate, and the dissolution of sedimentary rocks, leading to an alteration in water taste. While not posing adverse effects generally, it can be impactful for vulnerable individuals [49]. In accordance with WHO standards, the permissible chloride level in potable water should not surpass 250 mg/L. Elevated chloride content imparts a salty taste to water. Findings reveal that chloride levels varied between 18 mg/L and 350 mg/L, with the highest concentrations observed in Sargodha at 350 mg/L, as depicted in Figure 4g.

Fluoride

Fluoride may be a natural contaminant that occurs naturally due to the weathering of rocks and percolating into the groundwater. Other sources are coal industries' deposition into the atmosphere, contributing to groundwater contamination. The recommended fluoride concentration is 1.5 mg/L, yet in the study region, certain samples, particularly in

Sargodha, surpassed the limits set by WHO. Findings indicate that the parameter ranged from 0.1 mg/L to 2.08 mg/L, as illustrated in Figure 4h.

Bicarbonate (HCO_3)

The dissolution of carbonate rocks is a common source of bicarbonate ions in the groundwater. Per WHO standards, the permissible limit for bicarbonate concentration in drinking water is 500 mg/L. Analysis of the study area revealed magnesium concentrations spanning from 122 mg/L to 560 mg/L. Notably, Sargodha (560 mg/L) and Lahore (532 mg/L) exhibited the highest values, as depicted in Figure 4i [47].

3.1.2. Heavy Metals

Arsenic

Arsenic is categorized as a hazardous metal. Water contamination due to arsenic is a concerning issue, not only in Pakistan but all over the globe. Arsenic can enter the supply due to anthropogenic activities, mainly dumping industrial effluents containing toxic metals directly into water channels. And it enters the supply naturally due to natural deposits of metal [50]. Heavy metal has been an emerging problem since the industrialization era. The arsenic level must not exceed ten mg/L as per WHO standards. The maximum value is observed in the study area for the Lahore division. Some areas of Sargodha and Faisalabad have strains of heavy metal pollution, as shown in Figure 4j.

Iron

Iron is found naturally, and its concentration is higher in groundwater than in surface water. The sources of groundwater contamination are weathering of the rock bearing the metal, untreated industrial effluents, and leachate from landfills [51]. For iron, the metal should not exceed 0.3 mg/L. In Sargodha, the samples exceed the permissible limit, showing a range of 0.2–9 mg/L, as shown in Figure 4k.

3.1.3. Microbiological Parameters

Drinking water contaminated with pathogens poses severe threats to human health as consuming the pathogenic contaminated water causes several diseases, including cholera, typhoid, fever, and hepatitis, various chronic health diseases. Water-borne diseases are due to the consumption of fecally contaminated water. For water quality assessment, microbial contamination is considered one of the critical parameters [52]. The high coliform levels in the Lahore and Sargodha divisions may be attributable to the discharge of untreated municipal wastewater from urban centers like Lahore city into groundwater bodies. The older water distribution infrastructure in these cities may also contribute to cross-contamination of drinking water supplies.

Total Coliforms

Coliforms are Gram-negative and rod-shaped bacteria found in the environment but are not spore-forming. For water quality monitoring, the types of bacteria (total coliforms, fecal coliforms) present the risk associated with each type [53]. Generally, total coliforms present in the water body indicate the extent to which the water supply is clean. According to the standards set by the WHO for drinking, the total coliform colonies must not be detected in any 100 mL sample of the water body [44]. The analysis showed that the results are similar for all parts of the study area. as for the Sargodha, Rawalpindi, Lahore, and some parts of the Gujranwala, as shown in Figure 4l. The findings are strongly supported by [54,55] for different cities in Punjab. The primary sources of the contamination of the microbes across the study area are municipal effluents, improper solid waste management, and open septic tanks [56].

E. coli

E. coli is the major indicator of fecal coliform contamination in the water compared to other members of the fecal group. The monitoring and assessment of the water quality primarily relies on *E. coli*. Some strains of this species can be harmful, while others are harmless [57]. According to the standards set by the WHO for drinking, the total coliform colonies must not be detected in any 100 mL sample of the water body [44]. The data analysis showed that the results are similar for all parts of the study area for Sargodha, Rawalpindi, Lahore, and some parts of Gujranwala, as shown in Figure 4m. Different cities in the Punjab Province support the findings.

The major sources of fecal contamination for *E. coli* are waste effluents, leakage of the sewerage systems, and improper laying of pipelines. Waste effluents are behind most microbial contamination, not only on the surface but also in the groundwater. The major recharging sources of groundwater include rivers, canals, and streams. They get polluted through the waste effluent and then percolate into the groundwater and contaminate it with microbes. The river Ravi in Lahore, the Lahore Canal, and Nullah Lai in Rawalpindi are major contributors to groundwater pollution [58].

3.1.4. Irrigation Parameters

Irrigation mainly relies on the availability of the minerals found in the groundwater, and many factors contribute to the ease of access to these minerals. These important parameters are.

(1) Electrical conductivity (EC).
(2) Sodium adsorption ratio (SAR).
(3) Residual sodium carbonate (RSC).

Electrical Conductivity (EC)

The water's electrical conductivity (EC) indicates the concentration of soluble salts in mg/L. Electrical conductivity tells us about the salinity hazard. Some physical properties of the water, such as odor and color, are associated with the EC concentration [59]. In the groundwater, the concentrated values of electrical conductivity are mainly due to the presence of ions of bicarbonates, sodium, and carbonates. According to the standards, the value for electrical conductivity should not exceed 1500 mg/L; the suitable range for crop yield is 750 mg/L [60]. The study area results show that electric conductivity ranged from 277 mg/L to 5717 mg/L. The highest values are observed in the Sargodha and some parts of Lahore, Rawalpindi, as shown in Figure 4n. The high electrical conductivity values are due to the contamination of the industrial effluents and excessive fertilizer use [61].

Sodium Adsorption Ratio (SAR)

The sodium adsorption ratio (SAR) is representative of sodium (Na^+) to calcium (Ca^+). The SAR typically indicates the sodium hazard. According to the standards, SAR must be within the permissible limits, and a suitable value is 5 for irrigated water [60]. The SAR value for the groundwater within the study area ranges from 0.22 to 5.8. The highest value was observed within Sargodha (5.8), as shown in Figure 4p.

Residual Sodium Carbonate (RSC)

The carbonate and bicarbonate content in the water is termed residual sodium carbonate. The high concentration of carbonate and bicarbonate increases the tendency of calcium precipitation, thereby increasing sodium in the soil and affecting crop yield [62]. According to the standards, the value for RSC should not exceed 2.5. The suitable range for crop yield is less than 1.25. The RSC value for the groundwater within the study area ranges from 0.31 to 4.3. The highest values are observed within Rawalpindi (4.3) and Sargodha (5.8), as shown in Figure 4o.

3.2. Comparison of Water Quality Parameters

For water quality assessment in the study area, 1094 data points were analyzed and compared with WHO standards, as shown in Table 3. The microbial contaminants were found to be the major contributor to groundwater pollution, with 27% and 19% of collected samples exceeding the threshold limits for total coliforms and *E. coli*, respectively, followed by arsenic (9%), iron (7%), and nitrate (6%) in the entire study area.

Table 3. Comparison of GW parameters with international standards.

Parameters	WHO Standards	Samples %Age Exceeding the Limit					
		Punjab	**Lahore**	**Rawalpindi**	**Gujranwala**	**Sargodha**	**Faisalabad**
Turbidity	1 NTU	5	1	5	3	1	3
PH	6.5–8.5	9	5	7	9	2	8
TDS	1000 mg/L	3	2	2	0	8	3
Total Hardness	120–180 mg/L	3	4	2	0	12	0
HCO_3	500 mg/L	1	0	0	0	6	1
Ca	75 mg/L	2	9	1	1	2	0
Mg	50 mg/L	2	0	9	0	4	2
Cl	250 mg/L	6	0	0	0	7	1
F	1.5 mg/L	4	3	7	0	3	0
Iron	0.3 mg/L	7	8	8	3	9	3
NO_3	50 mg/L	6	3	6	0	10	5
NO_2	3 mg/L	1	0	0	0	0	3
As	10 mg/L	9	25	1	2	5	0
T. coliform	0/100 mL	27	31	27	14	24	19
E. coli	0/100 mL	19	10	21	6	20	16
F. coliform	0/100 mL	18	20	17	9	7	9

Significant arsenic and microbial problems were detected in the Lahore division at 25% and 31%, respectively. The Rawalpindi and Gujranwala samples depicted higher values (exceeding) than the standards. Sargodha is the most polluted zone of the study area with microbial (19%), heavy metals (9%), and hardness (12%) issues that might be due to the open septic tanks, poorly managed sewerage system along the water supply lines, improper dumping of the waste [63]. Nitrate levels exceeding the WHO limit of 50 mg/L in the Sargodha division may pose health risks if the groundwater is used as a drinking source without adequate treatment. The high nitrate concentrations are also indicative of agricultural runoff in rural areas. Furthermore, the analysis of physiochemical parameters revealed that pH, alkalinity, hardness, and turbidity levels in the majority of areas were within the acceptable limits of WHO standards. It is worth mentioning that the pH value in Lahore slightly exceeded the threshold by a few points, with index values falling into different classification scales. Analysis across the study area revealed that 27% of samples exceeded the WHO microbiological thresholds, indicating widespread fecal contamination, while 9% surpassed recommended arsenic limits, posing heavy metal risks. Elevated nitrate levels above permissible standards were detected in 6% of tested sites, signifying agricultural impacts.

Class fair (65–79) covers 62.5% of the entire region, while a small portion is 2.5% of the class (95–100) [64].

Relative Proportions of Parameters

The groundwater quality parameters are categorized into different classes to evaluate relative proportions. The parameters are classified into the physiochemical, ions and metals (further into the anions, cations), heavy metals (Arsenic, Iron), and microbiology (Total coliforms, fecal coliforms, *E. coli*) as shown in Figure 5.

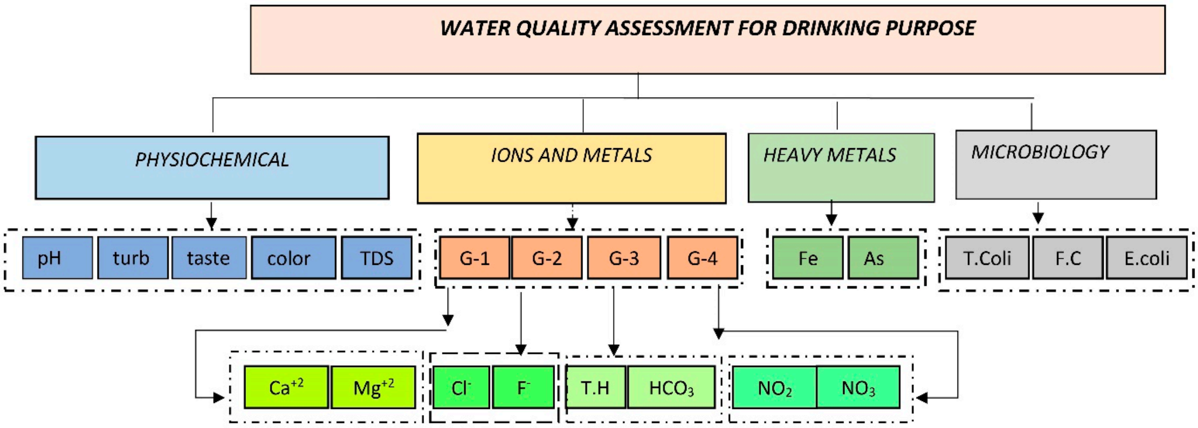

Figure 5. Pairs of different groundwater quality parameters.

In the first class, the dominant parameter is pH in the study area, as shown in Figure 6, while in the ions and metals, the relative proportions of the parameters are calcium (28%), fluoride (21%), and nitrate (14%), as shown in Figure 6b, and heavy metals with As (63%) and Fe (37%), as shown in Figure 6c. The microbial parameters show the proportions in Figure 6d as *E. coli* (53%), total coliforms (35%), and fecal coliforms (12%).

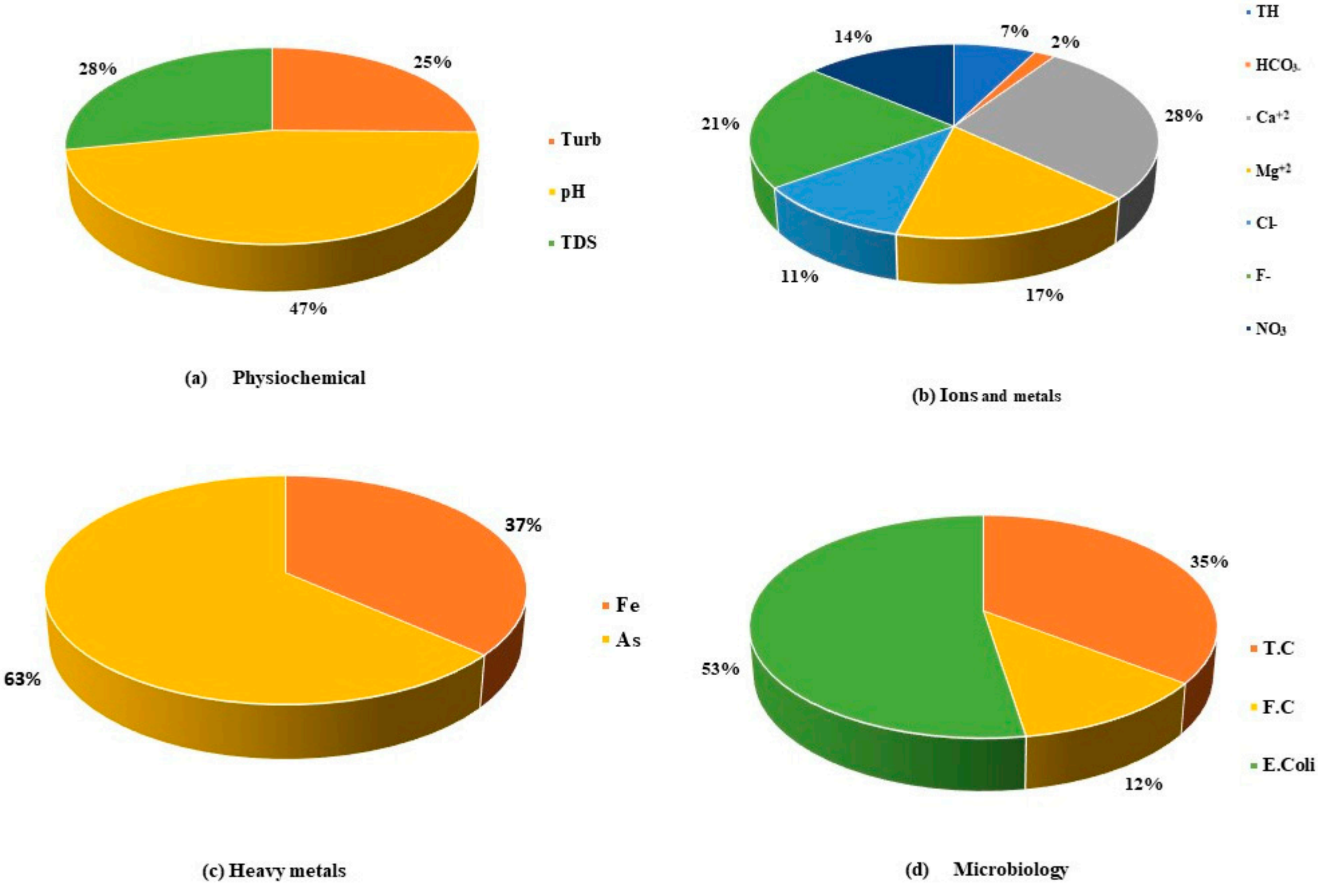

Figure 6. Relative proportion of different parameters.

3.3. Water Quality Index

The water quality index is calculated for different groundwater quality parameters, followed by the normalization of these selected parameters. The AHP-GWQI was computed using Equation (6).

3.3.1. Groundwater Quality Assessment for Drinking Purpose

Twenty-one (21) parameters were used to compute the WQI for drinking purposes using the AHP. The computed WQI was classified into five classes (excellent, good, medium, bad, and very bad), as shown in Table 4 [23].

Table 4. Range of the water quality index specified for drinking purposes.

Class	Index	Category Rank	Interpretation
I	0–50	Excellent	Can be safely used.
II	50–100	Good	Generally safe to use
III	100–120	Medium	Can be used for drinking
IV	120–150	Bad	Proper treatment is required before use
V	>150	Very Bad	Unsuitable

The indices were evaluated for five divisions. The index values show that the major part (38.54%) lies in class IV, while a small area (11.53%) covers class II. In the study area, no part reflects the groundwater quality of class I. According to the AHP-GWQI, the highest value for the index was computed for Sargodha (122.99), Lahore (122.925), and Rawalpindi (121.261), as shown in Figure 7a.

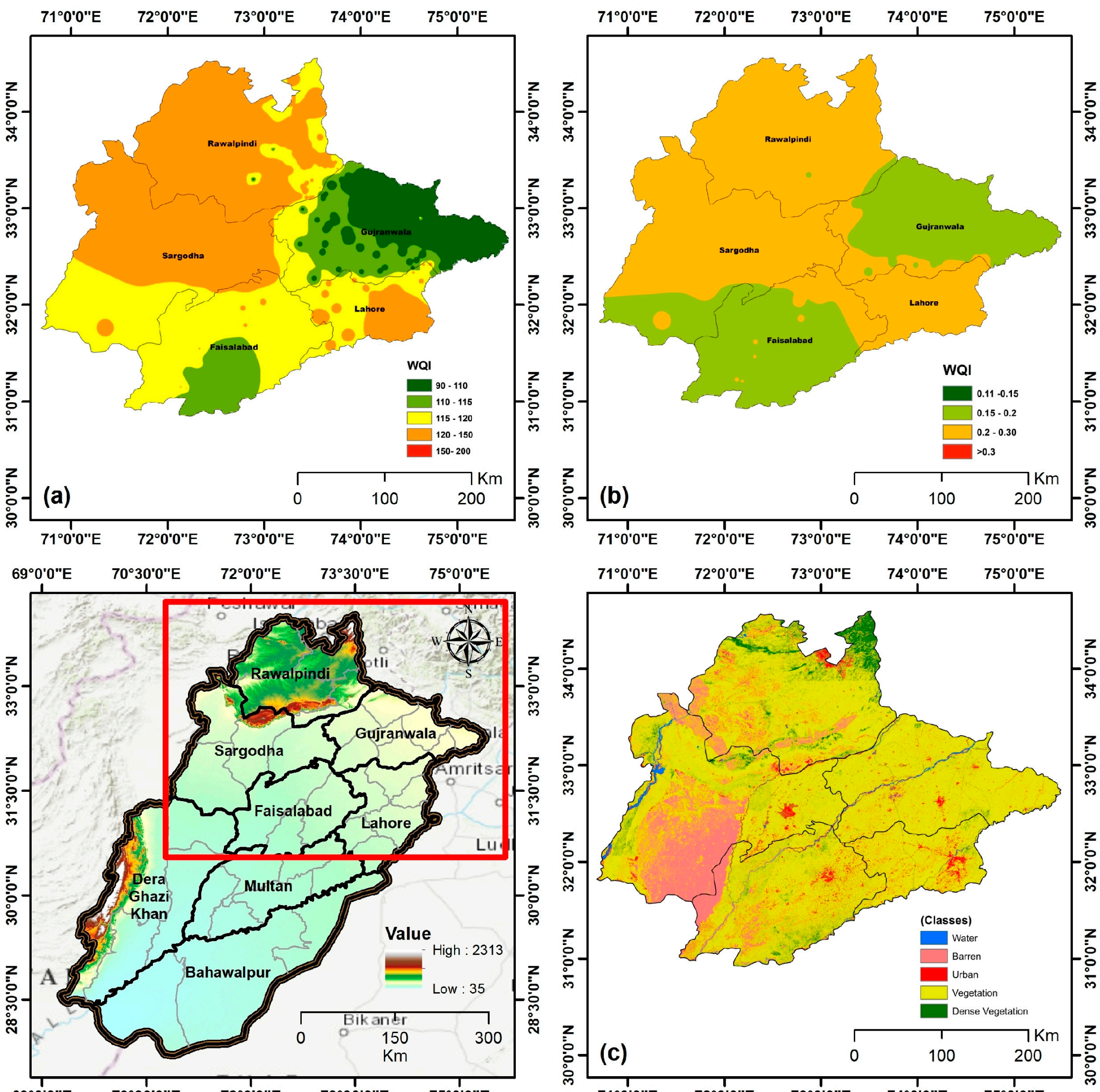

Figure 7. Water quality index (**a**) WQI for drinking, (**b**) WQI for irrigation, (**c**) land use land cover map.

Utilizing the NSFWQI, the majority of the Gujranwala area was generally classified as "good", with the exception of certain locations near industrial zones [65]. The assessment of the WQI in the Rawalpindi and Islamabad regions revealed that 23% of the groundwater samples were classified as "excellent water", 27% as "good water", 45% as "poor water", and 1% as "very poor water." The elevated poor water quality was observed in proximity to wastewater discharge points [66]. In the Sheikhupura region, fourteen (14) parameters were utilized to calculate the WQI. The computed values were then categorized into three groups: excellent (<50), good (50–100), and poor (100–200). The predominant portion of the area falls within the good water quality category, encompassing 65.577%, while 34.396% of the tehsil's area falls into the poor water quality category [67].

3.3.2. WQI for Irritation Purpose

The WQI for irrigation purposes was calculated based on three (03) parameters, namely EC, SAR, and RSC. The resulting groundwater quality index was categorized into four classes: excellent, good, permissible, and unsuitable [16], as shown in Table 5.

Table 5. Range of the water quality index specified for irrigation purposes.

Class	Index Value	Category Rank	Interpretation
I	0–0.1	Excellent	Can be safely used
II	0.1–0.2	Good	Generally safe to use as Irrigation water
III	0.20–0.30	Permissible	Suitable for irrigation of plants with salts tolerance
IV	>0.3	Unsuitable	Not suitable to use as IW

The index value shows that the major part (69.18%) lies in class III, permissible, while the remaining part (30.82%) falls into class II, good. The highest index value was computed for Rawalpindi (0.29), Lahore (0.28), and Sargodha (0.21), as shown in Figure 7b.

Unplanned urbanization and conversion of agricultural land to industrial regions are the major causes of water quality deterioration. While comparing the land use land cover map of the study area, it is dually noted that groundwater quality index values are higher in the urbanized areas, as shown in Figure 7. Regions with higher pollution indexes aligned with urban built-up areas, likely due to the contamination from anthropogenic activities. Areas with deeper groundwater levels tended to have better water quality.

Lahore, part of the study area, is the second largest metropolitan city of Punjab, and it has more severe drinking water quality issues. The water supply-demand chain is balanced by extracting groundwater 54 at a depth of 120–200 m for domestic and industrial purposes [6]. The groundwater stress zone is created because of groundwater overexploitation, as resource recharging is minimal. The aquifer of Lahore has been under ongoing stress because of rising groundwater demand generated by the city's accelerating unplanned extension and declining aquifer recharge. Due to land-use changes, industrial growth, and continued expansion, the deterioration of groundwater quality is continuously addressed. The depth of the aquifer around and under the city extends far down since the depth of wells has been increased in the quest for relatively good quality water extraction [68].

Rawalpindi's water needs have depended solely on the Rawal dam since 2000, and the catchment area is affected by rapid urbanization (increased by 85%) [69].

The availability of groundwater with quality is severe in the study area. There needs to be more proper management of the urbanized areas, monitoring resources, and implementation of the developed policies.

3.4. Development of the Mitigation Scenarios

Water pollution, which contaminates water resources, including surface and groundwater, is a significant concern [70]. The main sources of groundwater contamination include municipal and industrial effluents (heavy metals) and agricultural discharges (ions, salts, fertilizers). Consuming contaminated water can lead to water-borne diseases.

Restoring natural water quality conditions is challenging and requires a comprehensive understanding of the physical, chemical, and microbiological parameters, as well as the processes affecting contaminant behavior. Different scenarios were developed to comprehend the impact of parameter variability on overall groundwater quality and assess pollution control measures.

3.4.1. Preventing Chemical Contamination

The most effective approach to control pollution is at its source. Control measures are designed based on processes that degrade natural resources. These scenarios aim to mitigate the consequences of hazardous activities, including industrial effluents, agricultural runoff, and municipal and domestic wastes.

Scenario I: Variations in Microbiological Parameters

Microbiological contamination is a rising problem, contributing to 27% of groundwater pollution. Controlling this pollutant is crucial because pathogenic contamination of drinking water poses severe health risks. Pathogen contamination can lead to diseases such as cholera, typhoid, hepatitis, and various chronic health issues [71].

The major sources of microbial contamination in the study area are municipal effluents, improper solid waste management, and open septic tanks [72,73]. Fecal contamination, particularly *E. coli*, results from waste effluents, sewerage system leaks, and improper pipeline installation [58]. Measures to control microbiological contamination include:

- Monitoring industrial effluent discharge points.
- Sequential treatment of wastewater before discharge.
- Installation of treatment plants in urban areas.
- Regular sewerage system monitoring.
- Avoiding open septic tanks and direct disposal in open channels.
- Regular quality monitoring of pipelines.
- Separating water supply lines from sewerage systems.
- Maintaining a safe distance between landfills and domestic wells.

By implementing these measures, groundwater pollution can be mitigated. Combining these measures with artificial recharging leads to positive results, as shown in Figure 8 as Figure 8a shows an impact of 10% reduction with 5% recharging on the polluted areas while Figure 8b exhibits a 20% reduction with 10% recharging minute and Figure 8c shows a 30% reduction with 15% recharging with comparatively prominent results in Lahore, Rawalpindi, and Sargodha.

Scenario II: Variations in Heavy Parameters

Heavy metal contamination, especially arsenic and iron, is a significant concern in various zones of the study area. Arsenic and iron contamination can occur due to industrial effluents, natural metal deposits [50,74], weathering of metal-bearing rocks, and leachate from landfills [55]. Control measures for heavy metal contamination include:

- Monitoring industrial effluent discharge points.
- Restricting industries near water channels.
- Sequential treatment of wastewater.
- Maintaining a safe distance between landfills and domestic wells.

These measures, combined with artificial recharging, result in the remediation of groundwater in contaminated areas. The effectiveness of these measures is shown in Figure 9 as Figure 9a shows an impact of 10% reduction with 5% recharging on the polluted areas while Figure 9b exhibits minor improvement with a 20% reduction with 10% recharging, and Figure 9c shows a 30% reduction with 15% recharging with comparatively prominent results in Lahore, Rawalpindi, and Sargodha.

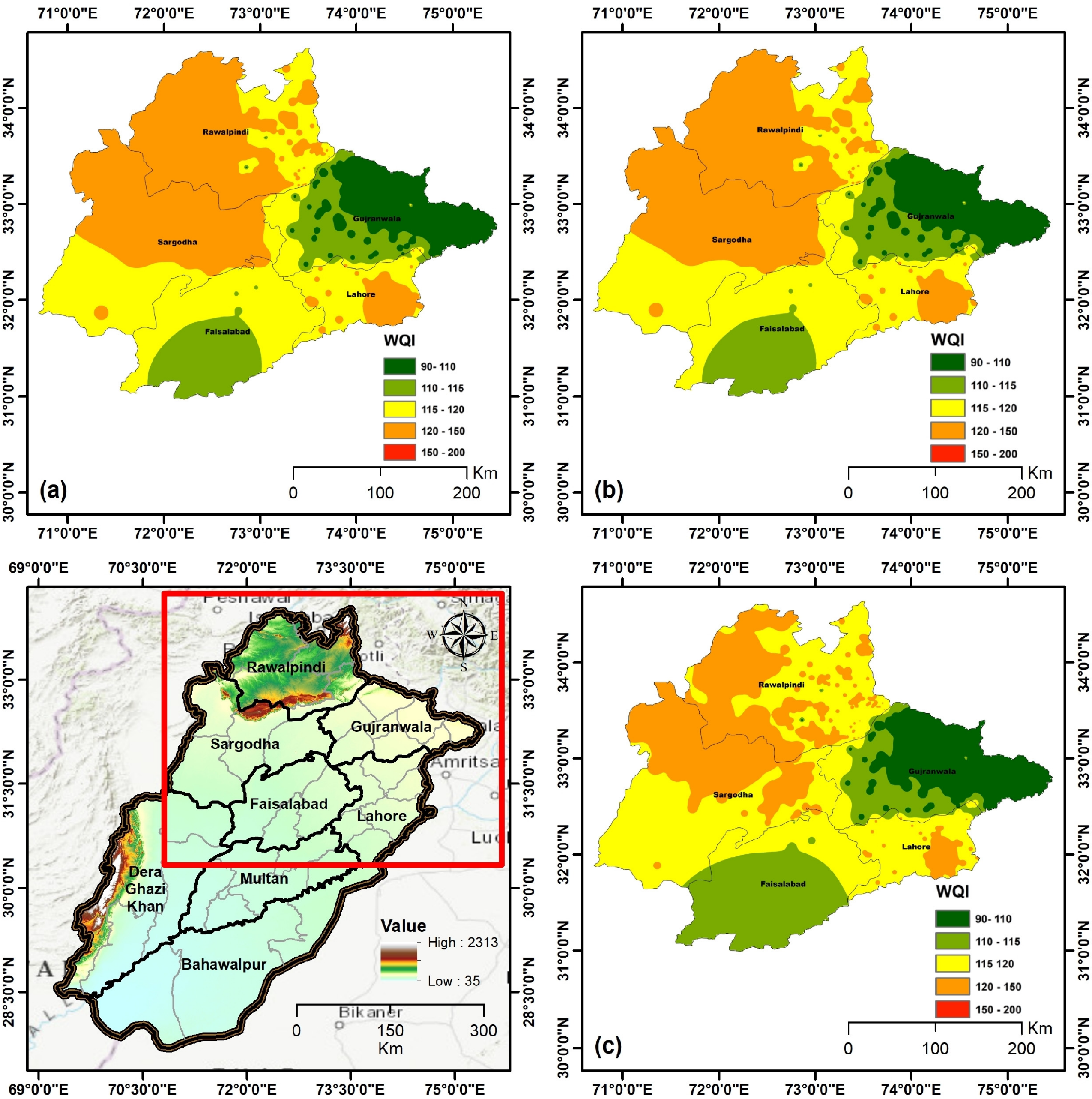

Figure 8. Scenario-I (variations in microbiological parameters): (**a**) 10% reduction with 5% recharging, (**b**) 20% reduction with 10% recharging, (**c**) 30% reduction with 15% recharging.

Scenario III (Variations in Chemical Parameters)

Groundwater chemistry is determined by various ions, including cations and anions. The study identified nitrate, fluoride, and hardness as ions deteriorating groundwater quality in parts of Sargodha, Lahore, and Rawalpindi. The major sources of contamination for these ions include the excessive use of nitrogen-based fertilizers, domestic effluents, and leakage of sewage systems [48]. Contamination sources for fluoride are industrial waste [75], leaching of rocks [76], and atmospheric deposition [76,77]. Control measures for chemical parameters include:

- Reducing the use of nitrogen-based fertilizers by 10% and 20%.
- Isolating drains from loaded areas.
- Providing highly contaminated areas with wastewater collection and treatment plants.
- Lining drainage channels to prevent seepage into groundwater.

These measures, combined with artificial recharging, lead to the remediation of groundwater in the contaminated areas. The effectiveness of these measures is illustrated in Figure 10 as Figure 10a shows an impact of a 10% reduction with 5% recharging on the polluted areas while Figure 10b exhibits a 20% reduction with 10% recharging per minute, and Figure 10c shows a 30% reduction with 15% recharging with comparatively prominent results in the Lahore, Rawalpindi, and Sargodha.

Overall, these scenarios aim to address the major sources of groundwater pollution, providing a comprehensive strategy for improving water quality in the study area.

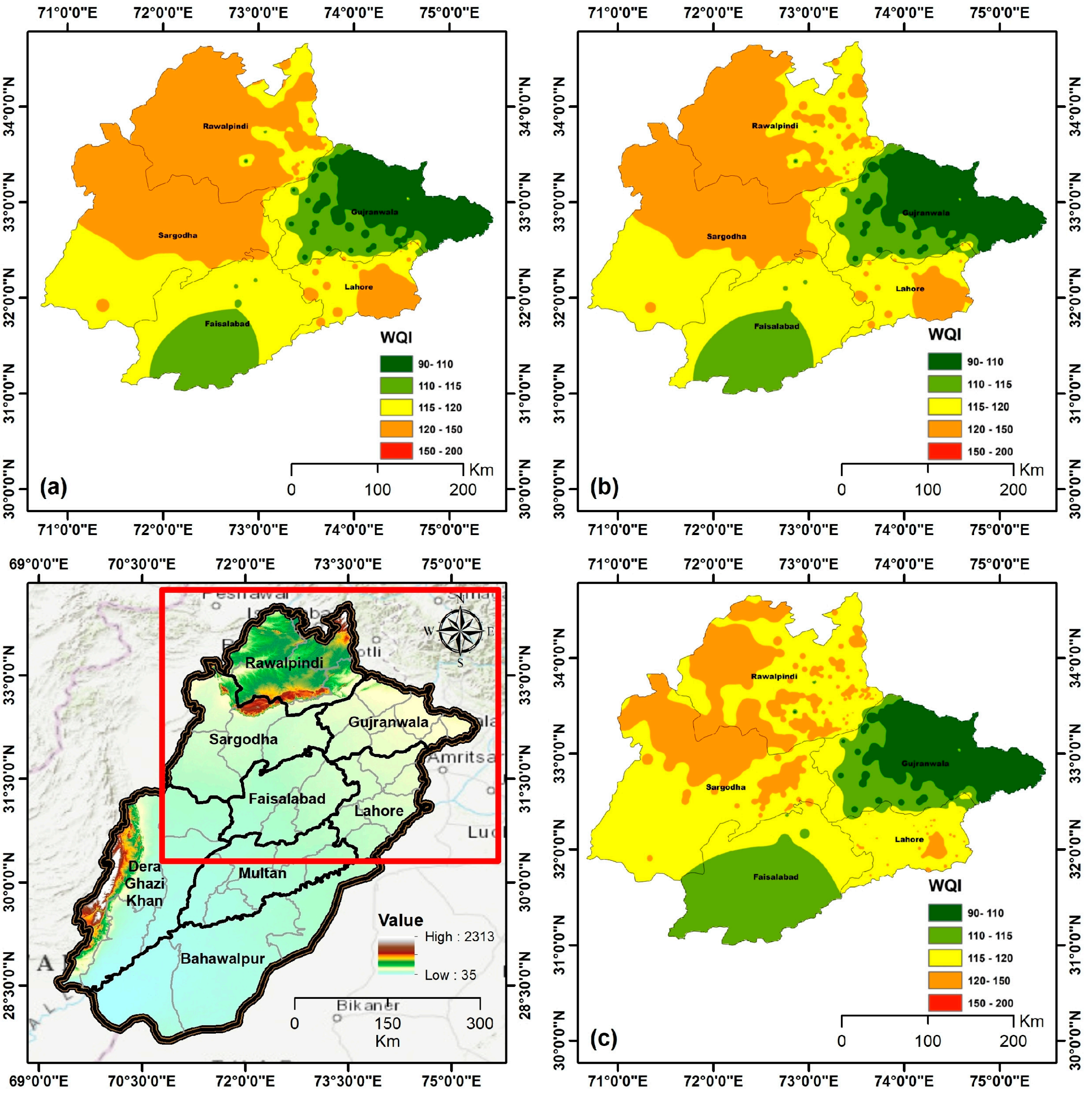

Figure 9. Scenario II (variations in heavy metals): (**a**) 10% reduction with 5% recharging, (**b**) 20% reduction with 10% recharging, (**c**) 30% reduction with 15% recharging.

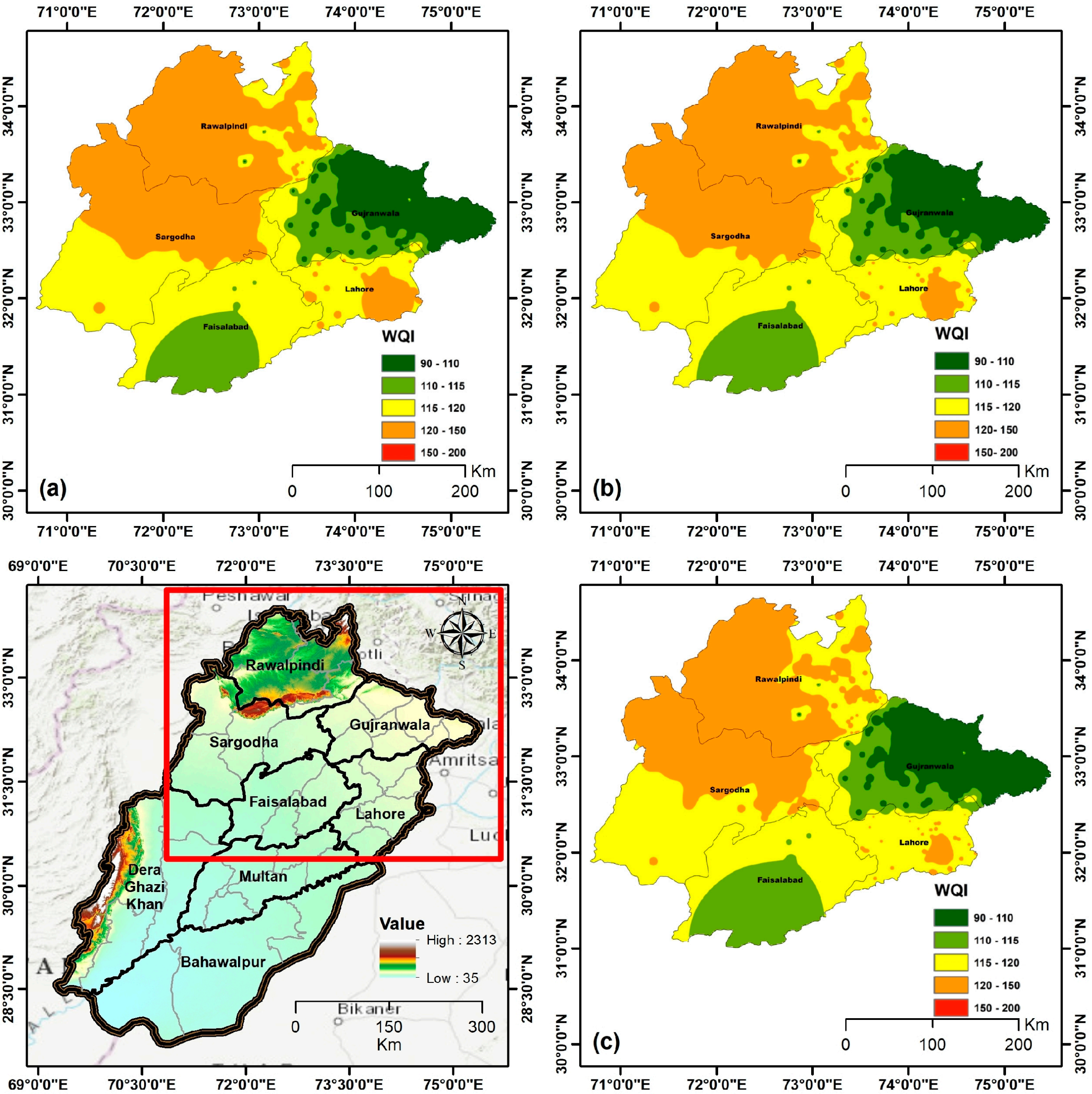

Figure 10. Scenario III (variations in chemical parameters): (**a**) 10% reduction with 5% recharging, (**b**) 20% reduction with 10% recharging, (**c**) 30% reduction with 15% recharging.

3.4.2. Treatment of Water to Reduce the Concentration of Chemical Contamination

The most primitive tool for controlling the pollution caused by different types of pollutants is wastewater treatment. It not only treats wastewater but also improves the environment's ecological aspects and conserves natural resources.

In Pakistan, the status of wastewater treatment is not much upgraded to the rate at which the pollution problem is increasing. The domestic and fecal wastes are directly discharged into the watercourses, internal septic tanks, and open fields. Only a few cities, including Karachi and Islamabad, have implemented wastewater treatment plants (biological) for municipal waste, but usually, municipal wastewater still needs to be treated. The pollution caused by industrial effluents is a significant problem and is still uncontrolled.

After the source control, the next challenge is the removal of the contaminants. Different scenarios are generated based on the water treatment approaches, taking note of literature as shown in Table 6 for the major pollutants (arsenic, microbiological contamination, nitrate) and evaluating their efficiencies as well as their impact on the final index of each polluted region of the study area.

Table 6. Wastewater treatment processes.

Process	Parameter	Percentage	Source
Primary treatment	TDS Bacterial loadings	40–60% 40–60%	[78]
Secondary treatment	TDS Bacterial loadings Hardness	65–80% 80–90% 45–55%	[78] [79]
Tertiary treatment	Arsenic Nitrate	>95% 75–86%	[80,81] [82]

Scenario I (Primary Treatment)

In this scenario, wastewater treatment in the primary stage is evaluated. The primary treatment is only efficient for removing the total dissolved solids (TDS) and bacterial loading, as shown in the figure. Three stages with different levels of treatment, as shown in Table 7, are established. Figure 11a exhibits results with a 40% reduction of the total dissolved solids (TDS) and bacterial loadings by wastewater treatment. Moreover, Figure 11b shows a treatment output of a 50% reduction in the total dissolved solids (TDS) and bacterial loadings from the wastewater with comparatively less obvious results in the polluted areas. Reduction of both pollutants by 60% is shown in part Figure 11c, with comparable results in Lahore, Sargodha, and some areas of Rawalpindi, as in Figure 11, and their impact on the computed indices shown in Table 7.

Table 7. Impacts of scenarios on the water quality index.

Areas	Scenarios						
	Primary Treatment			Secondary Treatment		Tertiary Treatment	
	S1	S2	S3	S1	S2	S1	S2
Lahore	121.77	121.43	120.94	120.99	120.43	120.13	119.96
Sargodha	122.86	122.75	121.72	121.48	120.99	120.50	119.12
Gujranwala	106.23	106.19	105.14	106.08	106.04	105.73	105.30
Rawalpindi	121.05	120.94	120.80	120.70	120.70	119.99	119.92
Faisalabad	113.80	113.64	112.32	113.70	112.88	113.00	112.19

Scenario II (Secondary Treatment)

In this scenario, wastewater treatment in the secondary stage is evaluated. The primary treatment is only efficient for removing the total dissolved solids (TDS) and bacterial loading, as shown in Figure 12. Two stages with different levels of treatment, as shown in Table 7, are established. Figure 12a exhibits results with a 65% reduction of the total dissolved solids (TDS), 80% bacterial loadings, and hardness reduced to 45% by the wastewater treatment. Moreover, Figure 12b shows the treatment output of an 80% reduction in the total dissolved solids (TDS), bacterial loadings up to 90%, and hardness by 55% from the wastewater. Reduction of these pollutants after treating the wastewater shows comparable results in the contaminated parts of Lahore, Sargodha, and some areas of Rawalpindi, and their impact on the computed indices is shown in Table 7.

Scenario III (Tertiary Treatment)

In this scenario, wastewater treatment in the tertiary stage is evaluated for the efficiency of removing the total dissolved solids (TDS) and bacterial loading, as shown in the figure. As shown in Table 7, two stages with different treatment levels are established. There was a reduction in the major pollutants, arsenic, with a 90% reduction, and the other main pollutant, nitrate, with a 75% reduction after treating the wastewater in Figure 13a. Figure 13b exhibits results with a 95% reduction in arsenic and nitrate, which was reduced by 85% from the wastewater treatment. The results improved the quality of the study area by 41%, following tertiary treatment as in Figure 13, and their impact on the computed indices is shown in Table 7.

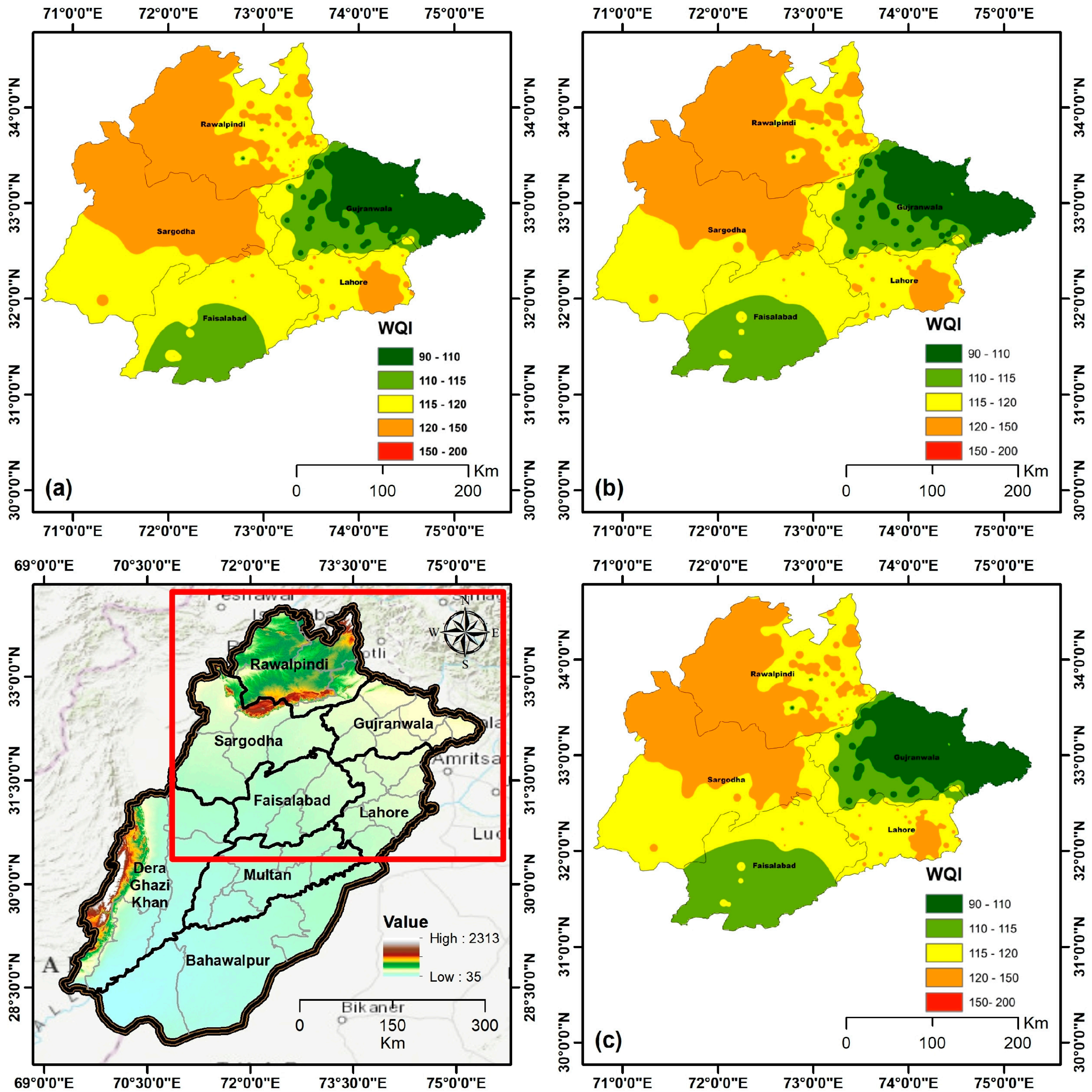

Figure 11. Scenario I (primary treatment): (**a**) 40% reduction (**b**) 50% reduction of the (TDS) and (**c**) bacterial loadings.

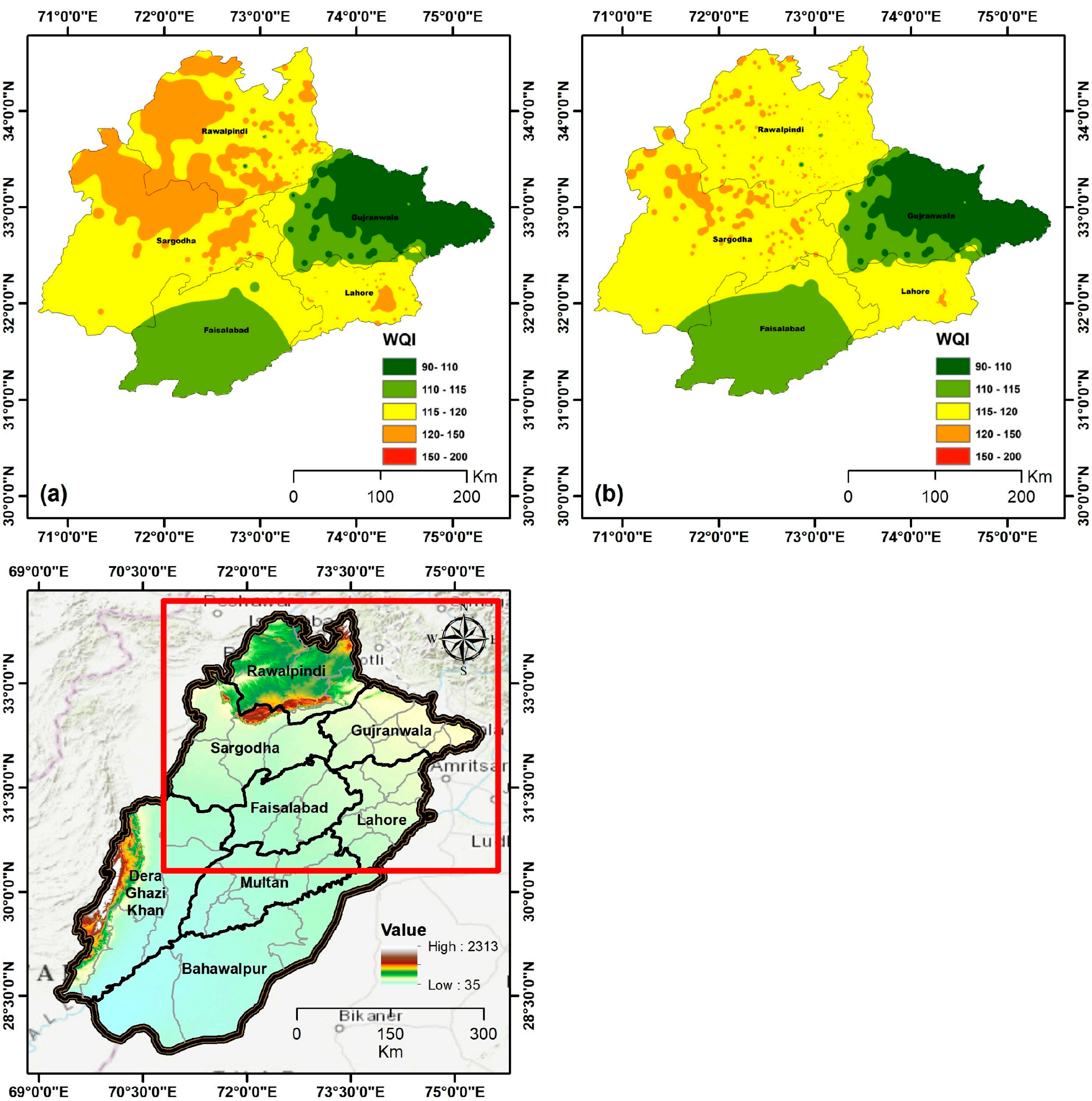

Figure 12. Scenario II (secondary treatment): Part (**a**) 65% reduction of the TDS, 80% bacterial loadings, and 45% hardness, (**b**) 80% reduction of TDS, 90% bacterial loadings, and 55% hardness.

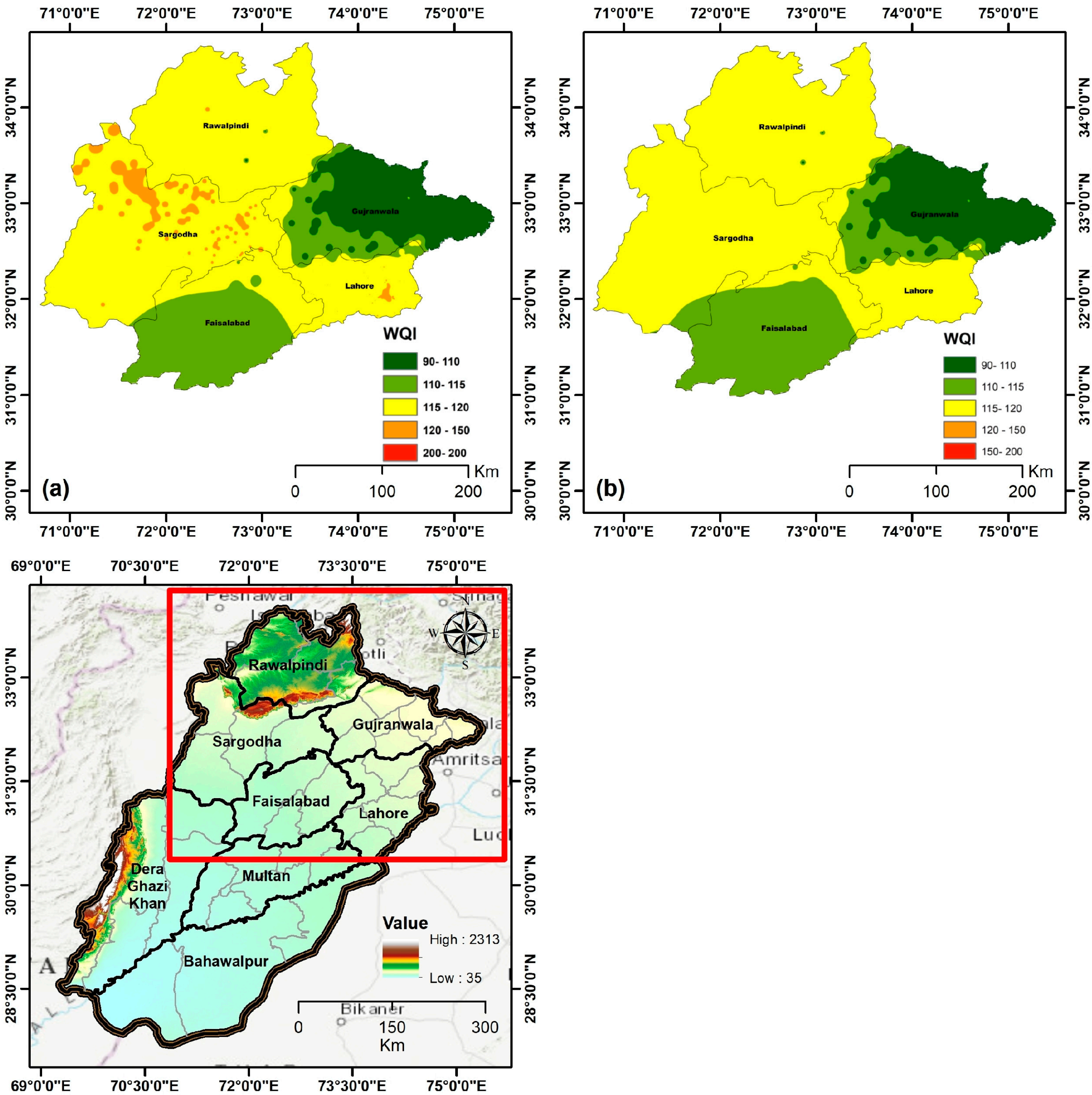

Figure 13. Scenario III (tertiary treatment): (**a**) Reduction by 90% Arsenic and nitrate 75% (**b**) Reduction by 95% Arsenic and nitrate 85%.

4. Discussion

This study comprehensively evaluated groundwater quality across the Punjab province by analyzing 24 key parameters at over 1094 sampling sites. The computed groundwater quality indices revealed discernible spatial patterns, with distinct problem areas in major urban centers and industrial zones.

Comparison of groundwater quality: The groundwater quality trends observed in this study, including severe microbiological and heavy metal contamination in the major urban centers of Lahore and Rawalpindi, along with high nutrient levels in agricultural areas, align with findings from previous localized assessments. For instance, a 2018 Lahore study reported 25% of groundwater samples having arsenic concentrations above WHO thresholds along with 31% showing coliform counts exceeding drinking water standards [83]. Similar or higher proportions of samples over limits were witnessed in the present statewide analysis. Likewise, 21% of samples in Rawalpindi were found to have *E. coli* contamination beyond permissible guidelines [84,85] as compared to 19% overall across the Punjab provinces. While providing statewide confirmation, the current results build upon these localized investigations on groundwater pollution sources and health hazards in key districts. The wider analytical frame, encompassing rural, urban, and industrial terrain, allows additional identification of regional patterns related to land use, hydrogeology, population clusters, and sanitation infrastructure. The widespread degradation of drinking and irrigation water quality revealed across Punjab mirrors groundwater management challenges confronted by urbanizing developing countries globally. As populations and economies grow, balancing water demand with sustainable use and conservation of subsurface reservoirs becomes imperative [86]. However, governance capacities rarely keep pace, resulting in uncontrolled extraction, inadequate sanitation infrastructure, and rampant contamination [87].

Correlation between LULC and groundwater pollution: The study reveals discernible associations between zones of intense urbanization and industrialization and severe deterioration in groundwater quality across key metrics. Microbiological and heavy metal contamination was pronounced in major cities like Lahore, Rawalpindi, and Sargodha, with high population densities, industrial growth, and the discharge of untreated wastes into hydrological bodies. In contrast, rural regions with agrarian land use showed heightened levels of fertilizer-derived nitrates and salts, indicative of agricultural runoff impacts. The composite LULC map illustrates the geographical overlap between urban built-up areas and pollution hotspots for both drinking and irrigation suitability indices. This correlation arises from multiple facets of anthropogenic activity. Unplanned urban expansion and industrialization increase concrete cover, hindering aquifer recharge while simultaneously elevating contamination loads from residential sewage, industrial effluents, and vehicular emissions. Groundwater over-extraction to satisfy municipal and industrial demands also compounds quality degradation [88]. Meanwhile, intensive fertilizer and pesticide use in croplands infiltrate subsurface reservoirs. An integrated management approach addressing pollution generation patterns from settlements, industries, and croplands in conjunction with groundwater conservation is imperative to restore and preserve quality. Punjab epitomizes this imbalance, with burgeoning pollution from industrial effluents, sewage discharges, agricultural runoff, and municipal wastes intensified by over-abstraction, as echoed in assessments across India, Bangladesh, and Africa [89]. Appropriate regulatory and technological interventions are urgently warranted. Our findings reiterate the need for discharge guidelines, real-time monitoring systems, and nature-based remediation [90], prioritizing key micropollutants and hotspots through a localized risk management approach [91].

Management scenarios effectiveness: The study formulates various pollution control and remediation scenarios encompassing upgrades to wastewater treatment, regulation of contaminant sources, and groundwater replenishment. The scenario analysis reveals that tertiary treatment of municipal wastewater, incorporating processes like filtration, disinfection, and nutrient removal, offers the highest rehabilitation potential, possibly restoring groundwater quality in 41% of the study region. Secondary treatment with sedimentation, biological digestion, and chlorination also indicates significant improvements by directly tackling microbial risks. However, the scope of these infrastructural interventions remains limited, given the distributed nature of contaminant generation. At least 27% of the study area requires targeted action to address microbiological risks through real-time water quality monitoring, separating distribution infrastructure from sewage lines, and managing aquifer recharge. The scenario testing provides a decision support foundation, illustrating that while centralized treatment plants will greatly assist quality restoration, localized precautions, onsite sanitation systems, and controlled agricultural application of agrochemicals are equally critical to containing the decline in quality. An adaptive strategy entailing wastewater upgrading along with rigorous contamination source oversight is essential for preserving groundwater usability.

Health risks: The heavy metal, nutrient, and microbiological contaminants detected across Punjab pose varying environmental and health consequences, underscoring the need for a risk-based mitigation approach. Microbiological pollution is the most widespread and alarming, given the acute gastrointestinal and longer-term effects linked to pathogens like *E. coli* and coliforms. With over a quarter of samples contravening WHO guidelines, addressing fecal contamination through water treatment and purified supply chains is an urgent priority. Likewise, heavy metal poisoning via arsenic and iron can prompt severe illnesses, from cardiovascular impacts to neurological disorders and cancers. While less pervasive currently, the high toxicity warrants stringent industrial regulation and monitoring. Excess nitrates and salts exhibit relatively lower health hazards but impede water potability and utility over time, meriting agricultural runoff control. A tiered strategy simultaneously tackling microbial risks, industrial metals, and non-point ions is essential, prioritizing actions based on the distinct public health threats. Monitoring must expand in high-risk urban and rural zones along with proactive mitigation where contamination already imperils water usability for drinking and irrigation. If business-as-usual resource depletion and contamination continue, over 50% of Punjab may have unusable groundwater by 2040, presenting risks to food security and public health. However, prospects exist for science-informed management to avoid the "tragedy of the groundwater commons" [92]. Structured governmental coordination, community participation, and adaptive policies on extraction limits, water pricing, and agricultural inputs can help balance utilization with sustainability [93].

Policy implications: The study exposes alarming groundwater quality deterioration trends, with under half of the areas analyzed as suitable for drinking without treatment. This decline directly threatens public health and agriculture, given the extensive dependence on subsurface reservoirs. Immediate policy interventions are vital to conserve current usability and prevent further damage. Stringent wastewater discharge guidelines need coupling with monitoring systems and pollution taxation. Simultaneously, groundwater extraction regulations can ease abstraction pressures alongside recharge enhancement programs. Agrochemical rules to moderate fertilizer and pesticide usage will mitigate a key diffuse source. Zonal delineation of groundwater pollution warrants tailored actions like prioritizing sewage infrastructure in microbial hotspots. Economic incentives and public education to reduce water demand and properly dispose of waste are equally important. Ultimately, an integrated policy mix addressing extraction, recharge, and multi-sectoral contamination while aligning stakeholders through incentives and awareness is essential to uphold long-term groundwater adequacy across residential, ecological, and livelihood needs. The study provides an evidentiary base to trigger the urgent adoption of science-based groundwater governance [94]. Specifically, two priority actions emerge from the study. Firstly, widespread water quality monitoring for microbiological and heavy metal hazards, given their acute health impacts. Secondly, aggressive centralized and decentralized wastewater treatment expansions to tackle industrial and municipal contamination. These measures, combined with conservation incentives, can restrict a further decline in this critical hidden resource [95].

Microbiological contamination emerged as the predominant issue, accounting for over a quarter of samples exceeding the WHO thresholds for total coliforms and *E. coli*. The contamination hotspots aligned closely with major cities like Lahore, Rawalpindi, and Sargodha, which have high population densities and discharge large volumes of untreated municipal wastewater into water bodies. Leakages from aging water supply and sewerage infrastructure likely contribute to the microbial pollution of groundwater reserves. Rural areas also exhibited fecal contamination, potentially due to onsite sanitation systems like pit latrines and septic tanks.

Heavy metals, especially arsenic, were found to be problematic in the Lahore division, indicative of industrial pollution from sectors like textiles, chemicals, and metal processing. The heavy metal contamination poses severe health risks and should be urgently addressed. Sargodha and Faisalabad divisions had localized traces of arsenic and iron contamination.

Ions and salts like nitrates, fluoride, and chloride exceeded thresholds mainly in the Sargodha division. Elevated nitrate concentrations imply the impacts of fertilizer runoff from intensive agriculture. Fluoride levels were also the highest in Sargodha, possibly due to fluoride-bearing geological formations. The broad spatial patterns suggest that microbiological and heavy metal pollution is most severe in urban-industrial zones, while ions and salts impact groundwater quality in rural agricultural areas.

The study revealed that areas with deeper groundwater tables and greater recharge from precipitation or surface water tended to have lower contamination levels. However, water quality is deteriorating in zones with heavy withdrawals for irrigation and potable supplies. As Punjab's population grows, groundwater abstraction can be expected to increase, exacerbating quality issues [96].

Mitigation strategies should prioritize upgrading wastewater treatment, regulating industrial discharges, and reducing fertilizer application. The scenario analysis indicated that the tertiary treatment of municipal wastewater could potentially rehabilitate 41% of the study area. Secondary treatment also showed significant improvements. However, 27% of the region requires measures to address microbiological contamination, such as regular water quality monitoring and separating water lines from sewage systems.

Overall, the study provided a robust baseline assessment of groundwater quality at the provincial scale, identifying priority areas and contamination sources. The results can guide the formulation and spatial targeting of groundwater management policies for safeguarding this vital but threatened resource. Monitoring of quality parameters needs to expand in conjunction with the stronger enforcement of water pollution regulations. Public awareness campaigns on water conservation and pollution impacts are also essential. An integrated approach combining supply augmentation, demand management, and water quality protection is imperative for the sustainability of groundwater reserves across Punjab [97].

5. Conclusions

This study conducted an integrated assessment of groundwater quality across the Punjab province, Pakistan, by analyzing 24 key parameters at over 1094 sampling sites. The analytical hierarchy process was employed to determine weights for the selected indicators, which were aggregated into a weighted WQI. The computed WQI layers were classified to delineate groundwater quality zones for drinking and irrigation suitability.

The results revealed that 27% of samples exceeded WHO thresholds for total coliforms, indicating widespread microbiological contamination attributed to untreated wastewater discharges in urban areas. Heavy metals, especially arsenic, emerged as a significant concern in the Lahore division. Elevated levels of ions and salts like nitrates and fluoride exceeded limits primarily in the Sargodha division, likely due to fertilizer runoff.

Overall, the WQI analysis found that 38.54% of the study area fell in the "bad" category, requiring treatment before potable use. Only 11.53% was classified as "good" quality. For irrigation, most of the region was classified as "permissible", but 30.82% was designated "good". The assessment showed deteriorating trends in groundwater quality, particularly near major cities. The computed groundwater quality indices revealed discernible spatial patterns, with distinct problem areas where drinking water standards were exceeded, posing risks for public health if supply is untreated. Targeted policies and treatment strategies focused on ensuring drinking water safety are critically needed to manage current quality issues documented across both urban and rural zones.

The scenario analysis indicated that upgrading wastewater treatment could potentially rehabilitate 41% of the study area if tertiary treatment is applied. Secondary treatment also showed improvements. However, targeted measures are essential to address microbiological contamination in 27% of the region.

The study provided a robust baseline evaluation of groundwater quality at the crucial provincial scale. The results can guide evidence-based policies for groundwater monitoring and pollution control. Integrated management encompassing water conservation, treatment upgrades, and stronger regulation is imperative to safeguard groundwater reserves. The methodology and findings furnish vital insights for assessing and preserving groundwater quality in other developing regions confronted with rapid urbanization and environmental degradation.

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References

1. USGS. *Where Is Earth's Water?* U.S. Geological Survey: Reston, VA, USA, 2016.
2. Foster, S.; Hirata, R.; Gomes, D.; D', M.; Paris, E.M.; Washington, D.C. *Groundwater Quality Protection: A Guide for Water Utilities, Municipal Authorities, and Environment Agencies*; The World Bank: Washington, DC, USA, 2002. [CrossRef]
3. Qureshi, A.S.; McCornick, P.G.; Sarwar, A.; Sharma, B.R. Challenges and Prospects of Sustainable Groundwater Management in the Indus Basin, Pakistan. *Water Resour. Manag.* **2010**, *24*, 1551–1569. [CrossRef]
4. WWF-Pakistan. *Pakistan's Water at Risk: Water and Health-Related Issues in Pakistan and Key Recommendations: A Special Report: IRC*; WWF-Pakistan: Lahore, Pakistan, 2007.
5. Aslam, R.W.; Shu, H.; Yaseen, A. Monitoring the Population Change and Urban Growth of Four Major Pakistan Cities through Spatial Analysis of Open Source Data. *Ann. GIS* **2023**, *29*, 355–367. [CrossRef]
6. Zhu, G.; Liu, Y.; Shi, P.; Jia, W.; Zhou, J.; Liu, Y.; Ma, X.; Pan, H.; Zhang, Y.; Zhang, Z.; et al. Stable Water Isotope Monitoring Network of Different Water Bodies in Shiyang River Basin, a Typical Arid River in China. *Earth Syst. Sci. Data* **2022**, *14*, 3773–3789. [CrossRef]
7. Vadde, K.; Wang, J.; Cao, L.; Yuan, T.; McCarthy, A.; Sekar, R. Assessment of Water Quality and Identification of Pollution Risk Locations in Tiaoxi River (Taihu Watershed), China. *Water* **2018**, *10*, 183. [CrossRef]
8. Yin, L.; Wang, L.; Li, J.; Lu, S.; Tian, J.; Yin, Z.; Liu, S.; Zheng, W. YOLOV4_CSPBi: Enhanced Land Target Detection Model. *Land* **2023**, *12*, 1813. [CrossRef]
9. Masood, N.; Batool, S.; Farooqi, A. Groundwater Pollution in Pakistan. In *Global Groundwater*; Elsevier: Amsterdam, The Netherlands, 2021; pp. 309–322.
10. Aslam, R.W.; Shu, H.; Yaseen, A.; Sajjad, A.; Abidin, S.Z.U. Identification of Time-Varying Wetlands Neglected in Pakistan through Remote Sensing Techniques. *Environ. Sci. Pollut. Res.* **2023**, *30*, 74031–74044. [CrossRef] [PubMed]
11. Bouslah, S.; Djemili, L.; Houichi, L. Water Quality Index Assessment of Koudiat Medouar Reservoir, Northeast Algeria Using Weighted Arithmetic Index Method. *J. Water Land Dev.* **2017**, *35*, 221–228. [CrossRef]
12. Chen, J.; Huang, Q.; Lin, Y.; Fang, Y.; Qian, H.; Liu, R.; Ma, H. Hydrogeochemical Characteristics and Quality Assessment of Groundwater in an Irrigated Region, Northwest China. *Water* **2019**, *11*, 96. [CrossRef]
13. Akhtar, N.; Ishak, M.I.S.; Ahmad, M.I.; Umar, K.; Md Yusuff, M.S.; Anees, M.T.; Qadir, A.; Almanasir, Y.K.A. Modification of the Water Quality Index (Wqi) Process for Simple Calculation Using the Multi-Criteria Decision-Making (Mcdm) Method: A Review. *Water* **2021**, *13*, 905. [CrossRef]
14. Sutadian, A.D.; Muttil, N.; Yilmaz, A.G.; Perera, B.J.C. Using the Analytic Hierarchy Process to Identify Parameter Weights for Developing a Water Quality Index. *Ecol. Indic.* **2017**, *75*, 220–233. [CrossRef]
15. Thungngern, J.; Wijitkosum, S.; Sriburi, T.; Sukhsri, C. A Review of the Analytical Hierarchy Process (AHP): An Approach to Water Resource Management in Thailand. *Appl. Environ. Res.* **2015**, *37*, 13–32. [CrossRef]
16. Kavurmacı, M.; Karakuş, C.B. Evaluation of Irrigation Water Quality by Data Envelopment Analysis and Analytic Hierarchy Process-Based Water Quality Indices: The Case of Aksaray City, Turkey. *Water Air Soil Pollut.* **2020**, *231*, 55. [CrossRef]

17. Jhariya, D.C.; Kumar, T.; Dewangan, R.; Pal, D.; Dewangan, P.K. Assessment of Groundwater Quality Index for Drinking Purpose in the Durg District, Chhattisgarh Using Geographical Information System (GIS) and Multi-Criteria Decision Analysis (MCDA) Techniques. *J. Geol. Soc. India* **2017**, *89*, 453–459. [CrossRef]
18. Aslam, R.W.; Shu, H.; Javid, K.; Pervaiz, S.; Mustafa, F.; Raza, D.; Ahmed, B.; Quddoos, A.; Al-Ahmadi, S.; Hatamleh, W.A. Wetland Identification through Remote Sensing: Insights into Wetness, Greenness, Turbidity, Temperature, and Changing Landscapes. *Big Data Res.* **2023**, *35*, 100416. [CrossRef]
19. Misaghi, F.; Delgosha, F.; Razzaghmanesh, M.; Myers, B. Introducing a Water Quality Index for Assessing Water for Irrigation Purposes: A Case Study of the Ghezel Ozan River. *Sci. Total Environ.* **2017**, *589*, 107–116. [CrossRef] [PubMed]
20. El Baba, M.; Kayastha, P.; Huysmans, M.; De Smedt, F. Evaluation of the Groundwater Quality Using the Water Quality Index and Geostatistical Analysis in the Dier Al-Balah Governorate, Gaza Strip, Palestine. *Water* **2020**, *12*, 262. [CrossRef]
21. Kavurmaci, M.; Üstün, A.K. Assessment of Groundwater Quality Using DEA and AHP: A Case Study in the Sereflikochisar Region in Turkey. *Environ. Monit. Assess.* **2016**, *188*, 258. [CrossRef]
22. Adimalla, N.; Taloor, A.K. Hydrogeochemical Investigation of Groundwater Quality in the Hard Rock Terrain of South India Using Geographic Information System (GIS) and Groundwater Quality Index (GWQI) Techniques. *Groundw. Sustain. Dev.* **2020**, *10*, 100288. [CrossRef]
23. Karnena, M.K.; Saritha, V. Evaluation of Spatial Variability in Ground Water Quality Using Remote Sensing. *Int. J. Recent Technol. Eng.* **2019**, *8*, 4269–4278. [CrossRef]
24. Al-Paruany, K.B. Creating a Drinking Water Quality Index (WQI) Map Using the Geographic Information System (GIS) Technique for Karbala City, Iraq. *Earth Environ. Sci.* **2018**, *9*, 153–166.
25. Amiri, V.; Rezaei, M.; Sohrabi, N. Groundwater Quality Assessment Using Entropy Weighted Water Quality Index (EWQI) in Lenjanat, Iran. *Environ. Earth Sci.* **2014**, *72*, 3479–3490. [CrossRef]
26. Rui, S.; Zhou, Z.; Jostad, H.P.; Wang, L.; Guo, Z. Numerical Prediction of Potential 3-Dimensional Seabed Trench Profiles Considering Complex Motions of Mooring Line. *Appl. Ocean Res.* **2023**, *139*, 103704. [CrossRef]
27. Majeed, S.; Rashid, S.; Qadir, A.; Mackay, C.; Hayat, F. Spatial Patterns of Pollutants in Water of Metropolitan Drain in Lahore, Pakistan, Using Multivariate Statistical Techniques. *Environ. Monit. Assess.* **2018**, *190*, 128. [CrossRef]
28. Shabbir, R.; Ahmad, S.S. Use of Geographic Information System and Water Quality Index to Assess Groundwater Quality in Rawalpindi and Islamabad. *Arab. J. Sci. Eng.* **2015**, *40*, 2033–2047. [CrossRef]
29. Bashir, N.; Saeed, R.; Afzaal, M.; Ahmad, A.; Muhammad, N.; Iqbal, J.; Khan, A.; Maqbool, Y.; Hameed, S. Water Quality Assessment of Lower Jhelum Canal in Pakistan by Using Geographic Information System (GIS). *Groundw. Sustain. Dev.* **2020**, *10*, 100357. [CrossRef]
30. Zafar, U.; Mobeen, M.; Rahman, G.; Ahmed, M.; Javaid Iqbal, M.; Author, C. Assessment and Analysis of Groundwater Reservoir Suitability for Drinking Purpose Using GIS Based Multi Criteria Decision Approach, a Case Study of Faisalabad City. *J. Biodivers. Environ. Sci.* **2017**, *11*, 1–11.
31. UNDP. *The Vulnerability of Pakistan's Water Sector to the Impacts of Climate Change: Identification of Gaps and Recommendations for Action*; UNDP: Islamabad, Pakistan, 2017.
32. Arshad, A.; Mirchi, A.; Vilcaez, J.; Umar Akbar, M.; Madani, K. Reconstructing High-Resolution Groundwater Level Data Using a Hybrid Random Forest Model to Quantify Distributed Groundwater Changes in the Indus Basin. *J. Hydrol.* **2024**, *628*, 130535. [CrossRef]
33. Aslam, R.A.; Shrestha, S.; Usman, M.N.; Khan, S.N.; Ali, S.; Sharif, M.S.; Sarwar, M.W.; Saddique, N.; Sarwar, A.; Ali, M.U.; et al. Integrated SWAT-MODFLOW Modeling-Based Groundwater Adaptation Policy Guidelines for Lahore, Pakistan under Projected Climate Change, and Human Development Scenarios. *Atmosphere* **2022**, *13*, 2001. [CrossRef]
34. Bai, B.; Rao, D.; Chang, T.; Guo, Z. A Nonlinear Attachment-Detachment Model with Adsorption Hysteresis for Suspension-Colloidal Transport in Porous Media. *J. Hydrol.* **2019**, *578*, 124080. [CrossRef]
35. Horton, R.K. An Index Number System for Rating Water Quality. *J. Water Pollut. Control Fed.* **1965**, *3*, 292–315.
36. Jiao, Y.; Zhu, G.; Meng, G.; Lu, S.; Qiu, D.; Lin, X.; Li, R.; Wang, Q.; Chen, L.; Zhao, L.; et al. Estimating Non-Productive Water Loss in Irrigated Farmland in Arid Oasis Regions: Based on Stable Isotope Data. *Agric. Water Manag.* **2023**, *289*, 108515. [CrossRef]
37. Cude, C.G. Oregon water quality index a tool for evaluating water quality management effectiveness. *J. Am. Water Resour. Assoc.* **2001**, *37*, 125–137. [CrossRef]
38. Zhou, G.; Li, W.; Zhou, X.; Tan, Y.; Lin, G.; Li, X.; Deng, R. An Innovative Echo Detection System with STM32 Gated and PMT Adjustable Gain for Airborne LiDAR. *Int. J. Remote Sens.* **2021**, *42*, 9187–9211. [CrossRef]
39. Juwana, I.; Muttil, N.; Perera, B.J.C. Indicator-Based Water Sustainability Assessment-a Review. *Sci. Total Environ.* **2012**, *438*, 357–371. [CrossRef] [PubMed]
40. Saaty, T.L. A Scaling Method for Priorities in Hierarchical Structures. *J. Math. Psychol.* **1977**, *15*, 234–281. [CrossRef]
41. Saaty, R.W. The Analytic Hierarchy Process-What It Is and How It Is Used. *Math. Model.* **1987**, *9*, 161–176. [CrossRef]
42. Dong, Y.; Zhang, G.; Hong, W.-C.; Xu, Y. Consensus Models for AHP Group Decision Making under Row Geometric Mean Prioritization Method. *Decis. Support Syst.* **2010**, *49*, 281–289. [CrossRef]
43. Sarkar, K.; Majumder, M. Application of AHP-Based Water Quality Index for Quality Monitoring of Peri-Urban Watershed. *Environ. Dev. Sustain.* **2020**, *23*, 1780–1798. [CrossRef]
44. WHO. *Water Quality and Health-Review of Turbidity: Information for Regulators and Water Suppliers*; WHO: Geneva, Switzerland, 2017.

45. Zhou, G.; Deng, R.; Zhou, X.; Long, S.; Li, W.; Lin, G.; Li, X. Gaussian Inflection Point Selection for LiDAR Hidden Echo Signal Decomposition. *IEEE Geosci. Remote Sens. Lett.* **2022**, *19*, 1–5. [CrossRef]
46. Jameel, A.A.; Sirajudeen, J. Risk Assessment of Physico-Chemical Contaminants in Groundwater of Pettavaithalai Area, Tiruchirappalli, Tamilnadu—India. *Environ. Monit. Assess.* **2006**, *123*, 299–312. [CrossRef]
47. Tian, H.; Huang, N.; Niu, Z.; Qin, Y.; Pei, J.; Wang, J. Mapping Winter Crops in China with Multi-Source Satellite Imagery and Phenology-Based Algorithm. *Remote Sens.* **2019**, *11*, 820. [CrossRef]
48. Samadi-Darafshani, M.; Safavi, H.R.; Golmohammadi, M.H.; Rezaei, F. Assessment of the Management Scenarios for Groundwater Quality Remediation of a Nitrate-Contaminated Aquifer. *Environ. Monit. Assess.* **2021**, *193*, 190. [CrossRef]
49. Shahzaman, M.; Zhu, W.; Ullah, I.; Mustafa, F.; Bilal, M.; Ishfaq, S.; Nisar, S.; Arshad, M.; Iqbal, R.; Aslam, R.W. Comparison of Multi-Year Reanalysis, Models, and Satellite Remote Sensing Products for Agricultural Drought Monitoring over South Asian Countries. *Remote Sens.* **2021**, *13*, 3294. [CrossRef]
50. Karim, M.M. Arsenic in Groundwater and Health Problems in Bangladesh. *Water Res.* **2000**, *34*, 304–310. [CrossRef]
51. Tian, H.; Pei, J.; Huang, J.; Li, X.; Wang, J.; Zhou, B.; Qin, Y.; Wang, L. Garlic and Winter Wheat Identification Based on Active and Passive Satellite Imagery and the Google Earth Engine in Northern China. *Remote Sens.* **2020**, *12*, 3539. [CrossRef]
52. Daniels, B.; Mesner, N. Drinking Water Fact Sheet: Coliform Bacteria. 2010. Available online: https://digitalcommons.usu.edu/extension_curall/511/ (accessed on 20 October 2023).
53. US-EPA. *Manual for the Certification of Laboratories Analyzing Drinking Water*; US-EPA: Washington, DC, USA, 2005.
54. PCRWR. *Annual Report*; PCRWR: Islamabad, Pakistan, 2006.
55. Yin, L.; Wang, L.; Li, T.; Lu, S.; Yin, Z.; Liu, X.; Li, X.; Zheng, W. U-Net-STN: A Novel End-to-End Lake Boundary Prediction Model. *Land* **2023**, *12*, 1602. [CrossRef]
56. Nabeela, F.; Azizullah, A.; Bibi, R.; Uzma, S.; Murad, W.; Shakir, S.K.; Ullah, W.; Qasim, M.; Häder, D.P. Microbial Contamination of Drinking Water in Pakistan—A Review. *Environ. Sci. Pollut. Res.* **2014**, *21*, 13929–13942. [CrossRef]
57. Qiu, D.; Zhu, G.; Bhat, M.A.; Wang, L.; Liu, Y.; Sang, L.; Lin, X.; Zhang, W.; Sun, N. Water Use Strategy of Nitraria Tangutorum Shrubs in Ecological Water Delivery Area of the Lower Inland River: Based on Stable Isotope Data. *J. Hydrol.* **2023**, *624*, 129918. [CrossRef]
58. Yin, L.; Wang, L.; Li, T.; Lu, S.; Tian, J.; Yin, Z.; Li, X.; Zheng, W. U-Net-LSTM: Time Series-Enhanced Lake Boundary Prediction Model. *Land* **2023**, *12*, 1859. [CrossRef]
59. Zaman, M.; Shahid, S.A.; Heng, L. Irrigation Water Quality. In *Guideline for Salinity Assessment, Mitigation and Adaptation Using Nuclear and Related Techniques*; Springer Nature: Berlin/Heidelberg, Germany, 2018; pp. 113–131. [CrossRef]
60. WWF. *National Surface Classification Criteria and Irrigation Water Quality. Guidelines for Pakistan*; WWF: Washington, DC, USA, 2007.
61. Zhang, P.; Liu, L.; Yang, L.; Zhao, J.; Li, Y.; Qi, Y.; Ma, X.; Cao, L. Exploring the Response of Ecosystem Service Value to Land Use Changes under Multiple Scenarios Coupling a Mixed-Cell Cellular Automata Model and System Dynamics Model in Xi'an, China. *Ecol. Indic.* **2023**, *147*, 110009. [CrossRef]
62. Zhou, G.; Liu, X. Orthorectification Model for Extra-Length Linear Array Imagery. *IEEE Trans. Geosci. Remote Sens.* **2022**, *60*, 1–10. [CrossRef]
63. Haydar, S.; Qasim, M.M. A Study of Water Quality of Sargodha City. *J. Eng. Appl. Sci.* **2013**, *13*, 110–117.
64. Ma, J.; Li, J.; Weng, L.; Ouyang, X.; Chen, Y.; Li, Y. Phosphorus-Enhanced and Calcium-Retarded Transport of Ferrihydrite Colloid: Mechanism of Electrostatic Potential Changes Regulated via Adsorption Speciation. *Environ. Sci. Technol.* **2023**, *57*, 4219–4230. [CrossRef]
65. Abbas, M.; Shen, S.L.; Lyu, H.M.; Zhou, A.; Rashid, S. Evaluation of the Hydrochemistry of Groundwater at Jhelum Basin, Punjab, Pakistan. *Environ. Earth Sci.* **2021**, *80*, 300. [CrossRef]
66. Raza, D.; Shu, H.; Khan, S.U.; Ehsan, M.; Saeed, U.; Aslam, H.; Aslam, R.W.; Arshad, M. Comparative Geospatial Approach for Agricultural Crops Identification in Interfluvial Plain—A Case Study of Sahiwal District, Pakistan. *Pak. J. Agric. Res.* **2022**, *59*, 567–578. [CrossRef]
67. Chen, H.; Ye, Q.; Wang, X.; Sheng, J.; Yu, X.; Zhao, S.; Zou, X.; Zhang, W.; Xue, G. Applying Sludge Hydrolysate as a Carbon Source for Biological Denitrification after Composition Optimization via Red Soil Filtration. *Water Res.* **2024**, *249*, 120909. [CrossRef]
68. Basharat, M. Groundwater Environment in Lahore, Pakistan. In *Groundwater Environment in Asian Cities: Concepts, Methods and Case Studies*; Butterworth-Heinemann: Oxford, UK, 2016; pp. 147–184. [CrossRef]
69. Khan, M.; Hina, S.; Ali, H. Impact of Urbanization on Water Resources of Pakistan: A Review. *NUST J. Eng. Sci.* **2019**, *12*, 1–8. [CrossRef]
70. Li, Q.; Lu, L.; Zhao, Q.; Hu, S. Impact of Inorganic Solutes' Release in Groundwater during Oil Shale In Situ Exploitation. *Water* **2022**, *15*, 172. [CrossRef]
71. Yang, M.; Wang, H.; Hu, K.; Yin, G.; Wei, Z. IA-Net$:$ An Inception–Attention-Module-Based Network for Classifying Underwater Images From Others. *IEEE J. Ocean. Eng.* **2022**, *47*, 704–717. [CrossRef]
72. Ayesha, A. Pollution of Water Bodies: Challenges and Strategies. *Environ. PIAIP-NESPAK Lahore* **2012**, *11*, 1087–1098.
73. Ahmad, A.; Ahmad, S.R.; Gilani, H.; Tariq, A.; Zhao, N.; Aslam, R.W.; Mumtaz, F. A Synthesis of Spatial Forest Assessment Studies Using Remote Sensing Data and Techniques in Pakistan. *Forests* **2021**, *12*, 1211. [CrossRef]
74. Rasheed, H.; Jaleel, F.; Nisar, M.F. Analyzing the Status of Heavy Metals in Irrigation Water in Suburban Areas of Bahawalpur City, Pakistan. *Am. Eurasian J. Agric. Environ. Sci.* **2014**, *14*, 732–738. [CrossRef]

75. Farooqi, A.; Masuda, H.; Firdous, N. Toxic Fluoride and Arsenic Contaminated Groundwater in the Lahore and Kasur Districts, Punjab, Pakistan and Possible Contaminant Sources. *Environ. Pollut.* **2007**, *145*, 839–849. [CrossRef] [PubMed]
76. EPA. *Fluoride in Drinking Water: A Scientific Review of EPA's Standards*; National Academies Press: Washington, DC, USA, 2006.
77. Farooqi, A.; Masuda, H.; Kusakabe, M.; Naseem, M.; Firdous, N. Distribution of Highly Arsenic and Fluoride Contaminated Groundwater from East Punjab, Pakistan, and the Controlling Role of Anthropogenic Pollutants in the Natural Hydrological Cycle. *Geochem. J.* **2007**, *41*, 213–234. [CrossRef]
78. Al-Rekabi, W.S.; Qiang, H.; Qiang, W.W. Improvements in Wastewater Treatment Technology. *Pak. J. Nutr.* **2007**, *6*, 104–110. [CrossRef]
79. Viero, A.F.; Mazzarollo, A.C.R.; Wada, K.; Tessaro, I.C. Removal of Hardness and COD from Retanning Treated Effluent by Membrane Process. *Desalination* **2002**, *149*, 145–149. [CrossRef]
80. Weerasundara, L.; Ok, Y.-S.; Bundschuh, J. Selective Removal of Arsenic in Water: A Critical Review. *Environ. Pollut.* **2021**, *268*, 115668. [CrossRef]
81. Korngold, E.; Belayev, N.; Aronov, L. Removal of Arsenic from Drinking Water by Anion Exchangers. *Desalination* **2001**, *141*, 81–84. [CrossRef]
82. Ayyasamy, P.M.; Shanthi, K.; Lakshmanaperumalsamy, P.; Lee, S.-J.; Choi, N.-C.; Kim, D.-J. Two-Stage Removal of Nitrate from Groundwater Using Biological and Chemical Treatments. *J. Biosci. Bioeng.* **2007**, *104*, 129–134. [CrossRef]
83. Umar, M.; Khan, S.N.; Arshad, A.; Aslam, R.A.; Khan, H.M.S.; Rashid, H.; Pham, Q.B.; Nasir, A.; Noor, R.; Khedher, K.M.; et al. A Modified Approach to Quantify Aquifer Vulnerability to Pollution towards Sustainable Groundwater Management in Irrigated Indus Basin. *Environ. Sci. Pollut. Res.* **2022**, *29*, 27257–27278. [CrossRef]
84. Ullah, A.S.; Rashid, H.; Khan, S.N.; Akbar, M.U.; Arshad, A.; Rahman, M.M.; Mustafa, S. A Localized Assessment of Groundwater Quality Status Using GIS-Based Water Quality Index in Industrial Zone of Faisalabad, Pakistan. *Water* **2022**, *14*, 3342. [CrossRef]
85. Shafeeque, M.; Hafeez, M.; Sarwar, A.; Arshad, A.; Khurshid, T.; Asim, M.I.; Ali, S.; Dilawar, A. Quantifying Future Water-Saving Potential under Climate Change and Groundwater Recharge Scenarios in Lower Chenab Canal, Indus River Basin. *Theor. Appl. Clim.* **2023**. [CrossRef]
86. Foster, S.; MacDonald, A. The 'Water Security' Dialogue: Why It Needs to Be Better Informed about Groundwater. *Hydrogeol. J.* **2014**, *22*, 1489–1492. [CrossRef]
87. Mustafa, F.; Bu, L.; Wang, Q.; Shahzaman, M.; Bilal, M.; Aslam, R.W.; Dong, C. Spatiotemporal Investigation of Near-Surface CO_2 and Its Affecting Factors Over Asia. *IEEE Trans. Geosci. Remote Sens.* **2022**, *60*, 1–16. [CrossRef]
88. Zhao, Z.; Islam, F.; Waseem, L.A.; Tariq, A.; Nawaz, M.; Islam, I.U.; Bibi, T.; Rehman, N.U.; Ahmad, W.; Aslam, R.W.; et al. Comparison of Three Machine Learning Algorithms Using Google Earth Engine for Land Use Land Cover Classification. *Rangel. Ecol. Manag.* **2024**, *92*, 129–137. [CrossRef]
89. Lapworth, D.J.; Nkhuwa, D.C.W.; Okotto-Okotto, J.; Pedley, S.; Stuart, M.E.; Tijani, M.N.; Wright, J. Urban Groundwater Quality in Sub-Saharan Africa: Current Status and Implications for Water Security and Public Health. *Hydrogeol. J.* **2017**, *25*, 1093–1116. [CrossRef]
90. Page, D.; Dillon, P.; Toze, S.; Bixio, D.; Genthe, B.; Jiménez Cisneros, B.E.; Wintgens, T. Valuing the Subsurface Pathogen Treatment Barrier in Water Recycling via Aquifers for Drinking Supplies. *Water Res.* **2010**, *44*, 1841–1852. [CrossRef]
91. Ahmed, K.M.; Bhattacharya, P.; Hasan, M.A.; Akhter, S.H.; Alam, S.M.M.; Bhuyian, M.A.H.; Imam, M.B.; Khan, A.A.; Sracek, O. Arsenic Enrichment in Groundwater of the Alluvial Aquifers in Bangladesh: An Overview. *Appl. Geochem.* **2004**, *19*, 181–200. [CrossRef]
92. Shah, T. Climate Change and Groundwater: India's Opportunities for Mitigation and Adaptation. *Environ. Res. Lett.* **2009**, *4*, 035005. [CrossRef]
93. Ross, A. Groundwater Governance in Australia, the European Union and the Western USA. In *Integrated Groundwater Management*; Springer International Publishing: Cham, Switzerland, 2016; pp. 145–171.
94. Jat Baloch, M.Y.; Zhang, W.; Chai, J.; Li, S.; Alqurashi, M.; Rehman, G.; Tariq, A.; Talpur, S.A.; Iqbal, J.; Munir, M.; et al. Shallow Groundwater Quality Assessment and Its Suitability Analysis for Drinking and Irrigation Purposes. *Water* **2021**, *13*, 3361. [CrossRef]
95. Shah, S.H.I.A.; Jianguo, Y.; Jahangir, Z.; Tariq, A.; Aslam, B. Integrated Geophysical Technique for Groundwater Salinity Delineation, an Approach to Agriculture Sustainability for Nankana Sahib Area, Pakistan. *Geomat. Nat. Hazards Risk* **2022**, *13*, 1043–1064. [CrossRef]
96. Tariq, A.; Qin, S. Spatio-Temporal Variation in Surface Water in Punjab, Pakistan from 1985 to 2020 Using Machine-Learning Methods with Time-Series Remote Sensing Data and Driving Factors. *Agric. Water Manag.* **2023**, *280*, 108228. [CrossRef]
97. Mary, R.; Nasir, R.; Alam, A.; Tariq, A.; Nawaz, R.; Javied, S.; uz Zaman, Q.; Islam, F.; Nawaz Khan, S. Exploring Hazard Quotient, Cancer Risk, and Health Risks of Toxic Metals of the Mehmood Booti and Lakhodair Landfill Groundwaters, Pakistan. *Environ. Nanotechnol. Monit. Manag.* **2023**, *20*, 100838. [CrossRef]