water

MDPI

Article

RETRACTED: Exploring Groundwater Quality Assessment: A Geostatistical and Integrated Water Quality Indices Perspective

Muhammad Umer Masood [1], Muhammad Rashid [2,3], Saif Haider [2,3], Iram Naz [2,3], Chaitanya B. Pande [3,4,5,*], Salim Heddam [6], Fahad Alshehri [3], Ismail Elkhrachy [7], Amimul Ahsan [8,9,*] and Saad Sh. Sammen [10]

1 Geological Engineering Department, Montana Technological University, Butte, MT 59701, USA
2 Centre of Excellence in Water Resources Engineering, University of Engineering and Technology, Lahore 54890, Pakistan; m.rashid.6122@gmail.com (M.R.); here.iram561@gmail.com (I.N.)
3 Abdullah Alrushaid Chair for Earth Science Remote Sensing Research, Geology and Geophysics Department, King Saud University, Riyadh 11451, Saudi Arabia; falshehria@ksu.edu.sa
4 New Era and Development in Civil Engineering Research Group, Scientific Research Center, Al-Ayen University, Nasiriyah 64001, Thi-Qar, Iraq
5 Institute of Energy Infrastructure, Universiti Tenaga Nasional, Kajang 43000, Malaysia
6 Faculty of Science, Agronomy Department, Hydraulics Division, University 20 Août 1955 Skikda, Route EL HADAIK, BP 26, Skikda 21000, Algeria; heddamsalim@yahoo.fr
7 Civil Engineering Department, College of Engineering, Najran University, King Abdulaziz Road, Najran 66454, Saudi Arabia; iaelkhrachy@nu.edu.sa
8 Department of Civil and Environmental Engineering, Islamic University of Technology (IUT), Gazipur 1704, Bangladesh
9 Department of Civil and Construction Engineering, Swinburne University of Technology, Melbourne, VIC 3122, Australia
10 Department of Civil Engineering, College of Engineering, University of Diyala, Baqubah 10047, Diyala Governorate, Iraq; saad123engineer@yahoo.com
* Correspondence: chaitanay45@gmail.com (C.B.P.); ashikcivil@yahoo.com (A.A.)

Citation: Masood, M.U.; Rashid, M.; Haider, S.; Naz, I.; Pande, C.B.; Heddam, S.; Alshehri, F.; Elkhrachy, I.; Ahsan, A.; Sammen, S.S. RETRACTED: Exploring Groundwater Quality Assessment: A Geostatistical and Integrated Water Quality Indices Perspective. *Water* **2024**, *16*, 138. https://doi.org/10.3390/w16010138

Academic Editor: Christos S. Akratos

Received: 28 October 2023
Revised: 19 December 2023
Accepted: 25 December 2023
Published: 29 December 2023
Retracted: 23 April 2024

Abstract: Groundwater is an important source of freshwater. At the same time, anthropogenic activities, in particular, industrialization, urbanization, population growth, and excessive application of fertilizers, are some of the major reasons for groundwater quality deterioration. Therefore, the present study is conducted to evaluate groundwater quality by using integrated water quality indices and a geospatial approach to identify the different water quality zones and propose management strategies for the improvement of groundwater quality. Groundwater quality was evaluated through the physicochemical parameters (pH, chloride (Cl^-), fluoride(F^-), iron (Fe^{-2}), nitrate ($NO_3{}^{-1}$), nitrite (NO_2), arsenic (As), total hardness, bicarbonate ($HCO_3{}^-$), calcium (Ca^{+2}), magnesium (Mg^{+2}), color, taste, turbidity, total dissolved solids (TDS)) and microbiological parameters including total coliforms, fecal coliforms, and Escherichia coli of samples collected from the water and sanitation agency (WASA) and urban units. Irrigation parameters crucial to the assessment, including (electrical conductivity (EC), residual sodium carbonates (RSC), and sodium adsorption ratio (SAR)), were also collected at more than 1100 sites within the study area of upper and central Punjab. After collecting the data of physicochemical parameters, the analysis of data was initiated to compute the water quality index for groundwater quality, a four-step protocol in which the Analytical Hierarchy Process (AHP) was used to determine the weights of selected parameters by generating a pairwise matrix, on the relative importance of parameters using the Satty scale. The index was then classified into five classes for quality assessment of drinking water (excellent, good, medium, bad, and very bad) and four classes for irrigation water quality assessment (excellent, good, permissible, and unsuitable). After computing the index values for drinking as well as irrigation purposes, the values were interpolated, and various maps were developed to identify the status of groundwater quality in different zones of the study area. Mitigation strategies for water pollution involve source control, such as monitoring industrial discharge points and managing waste properly. Additionally, treating wastewater through primary, secondary, or tertiary stages significantly improves water quality, reducing contaminants like heavy metals, microbiological agents, and chemical ions, safeguarding water resources. The

This paper has been retracted. A retraction notice was published on 23 April 2024 in *Water* **2024**, *16*, 9. https://doi.org/10.3390/w16091195

findings highlight significant regional variations in water quality issues, with heavy metal concerns concentrated notably in Lahore and widespread emerging microbiological contamination across all studied divisions. This suggests a systemic problem linked to untreated industrial effluents and poorly managed sewerage systems. The computed indices for the Lahore, Sargodha, and Rawalpindi divisions indicate water quality ranging from marginal to unfit, underscoring the urgency for remediation. Conversely, other divisions fall within a medium class, potentially suitable for drinking purposes. Notably, microbiological contamination at 27% poses a major challenge for water supply agencies, emphasizing the critical need for pre-disposal primary, secondary, and tertiary treatments. These treatments could potentially rehabilitate 9%, 35%, and 41% of the study area, respectively, pointing toward tangible, scalable solutions critical for safeguarding broader water resources and public health. With the current pace of water quality deterioration, access to drinking water is a major problem for the public. The government should prioritize implementing strict monitoring mechanisms for industrial effluent discharge, emphasizing proper waste management to curb groundwater contamination. Establishing comprehensive pre-disposal treatments, especially primary, secondary, and tertiary stages, is imperative to address the prevalent heavy metal and microbiological issues, potentially rehabilitating up to 41% of affected areas. Additionally, creating proactive policies and allocating resources for sustainable groundwater management are crucial steps for ensuring broader water resource security and public health in the face of deteriorating water quality. Therefore, urgent regional action is needed to address escalating anthropogenic threats to groundwater, emphasizing the crucial need for proactive measures to safeguard public health and ensure sustainable water resources.

Keywords: groundwater; water quality; analytical hierarchy process; water quality indices; GIS; remote sensing

1. Introduction

Groundwater, vital for various purposes like agriculture, drinking water, and industry, faces a decline in quality due to a combination of natural factors and diverse human activities [1–3]. For this reason, groundwater quality evaluation is crucial for society. An assessment of the physical, biological, and chemical characteristics of water is made in connection to its intended usage, its intended quality, and any potential human influences on aquatic ecosystem health [4–6]. Waterborne infections continue to be risky for the vast majority of the world's population [7]. Numerous reports of drinking water contamination and the possible health dangers they pose in various parts of Pakistan can be found in the scholarly literature [8–12]. Water pollution originates from diverse sources, with agrochemicals including pesticides and fertilizers from agricultural activities, biological agents encompassing pathogens from sewage and livestock waste, and heavy metals such as lead, mercury, and arsenic from industrial discharges and mining activities. These distinct factors significantly contribute to the degradation of water quality in various ecosystems. [13–15]. Water quality assessments, crucial for identifying pollution issues and planning remedies to prevent waterborne illnesses, utilize the Water Quality Index (*WQI*) to categorize samples into understandable acceptability groups, aiding both the public and policymakers in comprehending the overall quality of drinking water from various sources like groundwater and surface water [16–22]. The Water Quality Index (*WQI*) is calculated by evaluating several water quality parameters, including physical, chemical, and biological characteristics. This method involves assigning weights to each parameter based on its significance to water quality. These parameters are then compared to standard values or thresholds set for ideal water quality. The calculation process typically involves normalizing the observed values of each parameter against its respective standard value or desirable range. After normalization, these values are aggregated or combined using mathematical equations or formulae to derive a single numerical value—the *WQI* score. This score provides a comprehensive snapshot of overall water quality, simplifying complex data into a single value that can be interpreted and communicated easily to stakeholders and the public. [23,24]. There are several ways described in the literature that may be used to calculate *WQI*, and these approaches can vary [25,26]. Numerous studies have shown how *WQI* may be integrated with geographic information systems to provide clear, readable maps of water suitability for a range of uses [27–30]. The distribution of environmental variables may be mapped using spatial interpolation techniques like Kriging [31,32]. Different environmental factors have been used by various researchers to illustrate the method's effectiveness [33–35]. Several studies have previously evaluated the usefulness of the different Kriging methods in mapping the geographical distribution of water quality metrics in contrast to other methods of interpolation [36–42].

Assessing groundwater suitability for human consumption involves analyzing its quality through various techniques, including the Water Quality Index (*WQI*), which condenses multiple chemical characteristics into a simplified score, aiding decision-makers and consumers in understanding its appropriateness for use [43]. To calculate *WQI* scores, several techniques have been presented [44]. An approach in which the ratios of the concentrations of the water quality measures and their suggested standard values are weighted and combined to provide a weighted *WQI* score is often employed. The weighted *WQI* technique has recently been used in investigations of groundwater quality [45–49]. The number of parameters (observations) utilized and their related weights vary for each technique used to compute *WQI* scores, but all approaches are identical in principle [50,51].

Unconfined aquifers are being contaminated by leaks from sewerage systems, untreated effluents, and landfill leachate. This is further complicated by rivers such as the Ravi River, previously a crucial recharge source, now acting as an effluent drain. Urbanization and reduced flow in the Ravi River have led to declining groundwater recharge, exacerbated by increased extraction to meet current and future water demands [52]. One of the most critical challenges in managing water resources is water quality. For decades, the quality of the world's water has been progressively deteriorating due to both anthropogenic and natural factors [53]. Before confirming groundwater's suitability for drinking, it is crucial to assess its quality across the three categories of chemical, biological, and physical parameters, considering both natural quality and intended usage, which can potentially impact the environment [54–57]. The objective for assessing the quality of water is to identify pollution sources and strategize for managing water resources to explain the water quality in a comprehensible manner while maintaining its scientific foundation [58]. Researchers face challenges in defining and communicating water quality due to its multifaceted parameters and influencing factors, despite utilizing various methods to support human well-being and community development [59,60].

The Water Quality Index (*WQI*) simplifies extensive water quality data into a single numerical value, offering an easily comprehensible measure. Widely embraced for its simplicity and scientific validity, it serves as a vital tool in evaluating and monitoring water quality worldwide [61]. Furthermore, as the pursuit of water quality assessment evolves, the integration of innovative technologies such as GIS emerges as a pivotal shift. This transition from traditional methods of assessing water quality to the realm of GIS-based approaches signifies a paradigmatic advancement in understanding and managing our water resources. The most common GIS applications in groundwater research are mapping and suitability assessments, measuring the vulnerability of groundwater, and analyzing quality using spatial data. The emergence of geographic information systems (GIS) has made the integration of multiple databases extremely simple. Before this, laboratory experiments were used to examine groundwater [62]. GIS integrates geostatistical methods to analyze spatial data, utilizing techniques like Kriging or IDW for predicting values at unsampled points. It creates maps displaying water quality parameters' spatial patterns and aids in assessing the suitability and vulnerability of areas. Essentially, GIS serves as a hub for geostatistical analyses, enabling visualizations and predictive modeling for informed decision-making in water resource management. GIS is revolutionizing research by providing valuable spatial mapping on water quality, enabling corrective actions, solutions to water challenges, assessment of availability, and monitoring of water quality status [63]. Groundwater is a vulnerable and crucial supply of irrigation and drinking water; it must be carefully maintained to keep its purity within acceptable standards. Groundwater degradation occurs primarily through the changes in its quality parameters beyond natural variability caused by the addition or removal of various contaminants. The effective management of groundwater-related phenomena of the resource is the key to ensuring the resource's long-term viability. The global concerns surrounding groundwater quality apply specifically to Lahore city, a region grappling with similar challenges. To address these issues in a localized context, this study aims to focus on Lahore's groundwater quality, employing comprehensive water quality indices and advanced geospatial methodologies. This research bridges a gap in the limited emphasis on specific localities, such as Lahore, within the broader context of global groundwater quality concerns. There is also a gap in exploring the direct linkage between deteriorating water quality, anthropogenic activities, and the lack of comprehensive, localized management strategies in the face of escalating contamination issues. Additionally, while the study highlights the utilization of various assessment techniques and technologies like GIS, there is a need for a more detailed exploration of the potential barriers or limitations in implementing these advanced methodologies specifically within the context of Lahore's groundwater quality management. Therefore, the present study aims to evaluate and assess the status of groundwater quality in Lahore city by using integrated water quality indices and a geostatistical approach. Thus, the aims of this study are to (1) assess the status of surface and groundwater quality utilizing water quality indices and geospatial approaches; and (2) develop varied strategies to enhance groundwater quality through the identification of distinct water quality zones.

2. Materials and Methods

2.1. Study Area

The study area, Punjab Province, which is situated in the semiarid lowlands zone at roughly latitude 27°53′34.53″ N to 33°4′8.33″ N and longitude 67°19′11.03″ E to 74°41′2.14″ E, is the largest province by population of Pakistan (Figure 1). Punjab's location in the Indian subcontinent's northwestern corner is of immense geographical and historical significance. To the west, northwest, and north, the region is bordered by high mountains.

The Punjab region comprises an alluvial plain structured by the Indus River with its major tributaries flowing into the southern part. The region is most probably recharged by the main rivers (the Ravi and Sutlej Rivers). The soil composition of the Punjab Plain is predominantly sand [64]. Cold winters and sultry summers categorize the semiarid and subtropical climate of the province with maximum and minimal annual temperatures of 31.9 °C and 18.2 °C, respectively. The rainfall distribution is widespread across the province. It receives 50–75% of its total rainfall during the monsoon season, predominantly linked to winds of the season [52]. Punjab's population is increasing exponentially. Between 1951 and 2017, the population of Punjab quadrupled from 20 million to 110.011 million [65]. Rapid urbanization, industrialization, unplanned consumption of groundwater, and lifestyle changes are increasing water demand [66] with water usage by the agriculture sector dominating other causes of the exponentially increased water consumption linked with the increased economic growth. Groundwater is a major contributor to meeting water supply demands. From 1976 to 2012, the dependency of irrigation on groundwater doubled, with most of the groundwater withdrawals for irrigation purposes occurring in Punjab, in the canal command areas, where 70% of private tube wells and others are dependent on groundwater-based irrigation [67]. Pakistan's major cities are mainly dependent on groundwater for their domestic purposes, with 70% of the drinking water for the total population of Pakistan being managed through groundwater [29]. The unavoidable thrust of increasing demand due to urban growth on available groundwater resources using direct extraction of groundwater or by extracting the water from a diversified network of canals in the cities to meet the demand will instantly instigate farmers to overexploite groundwater resources. Under these circumstances, the ever-growing population leads to an increase in the domestic water demand affecting the agricultural sector water schedules [68].

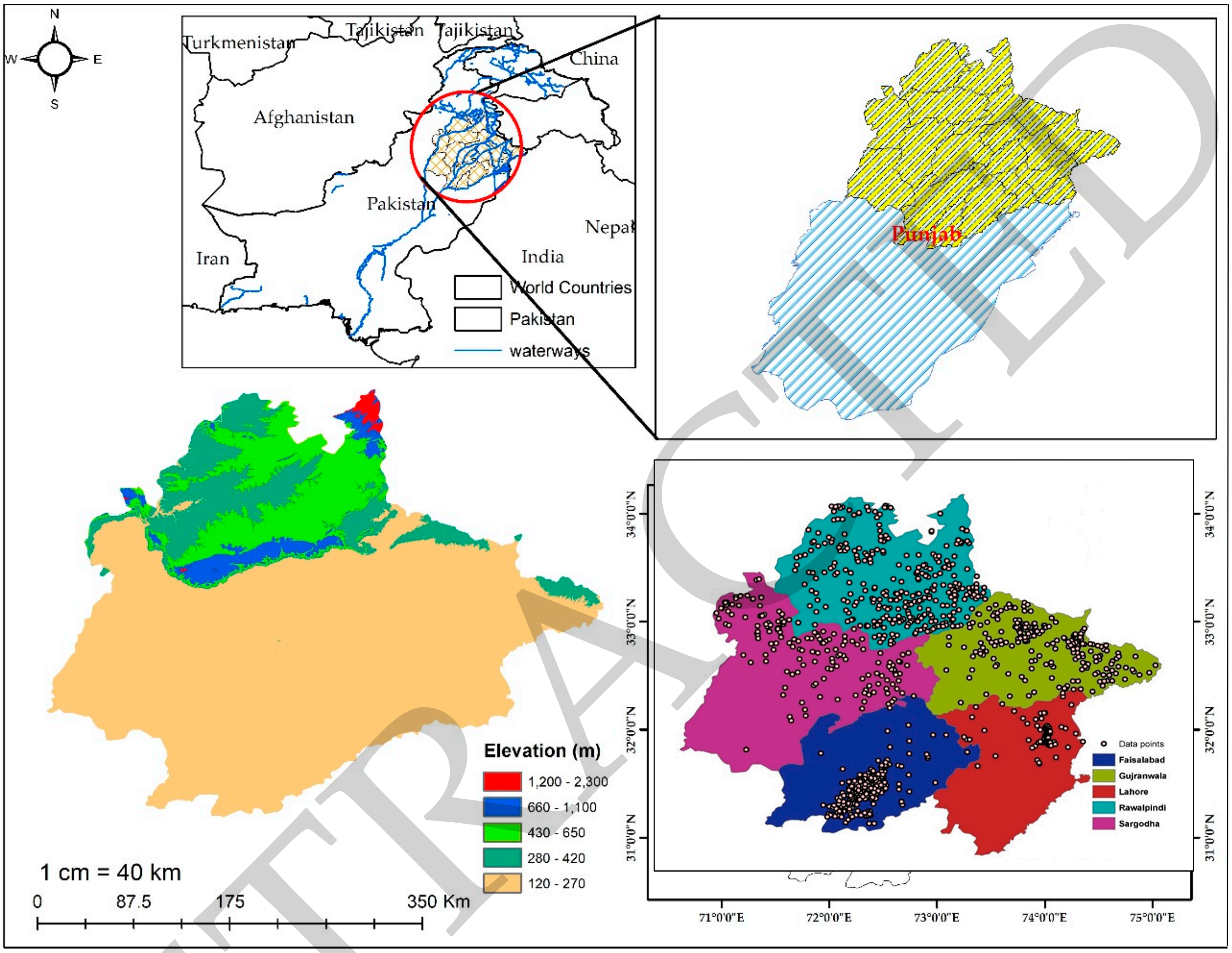

Figure 1. Map of the Study Area. The blue area shows the Punjab province of Pakistan boundary and the yellow part is the study area, part of Punjab. In this study, some area of Punjab was studied.

Bhatti et al. [69] studied the forecasting of the demand for water under changing socio-economic circumstances for quantifying the urban water demand conditions. In Faisalabad, Lahore, and Rawalpindi, the authors performed a survey of domestic water use in 80 to 100 urban households in both low- and high-income categories. There was a wide range of usage, with high-income groups' water demand being around double that of low-income groups. For fulfillment of industrial water demand, groundwater is the main source of all major industries except for some areas that are dependent on surface water. Around 80% of the water-demand supply chain for the industrial sector is balanced through groundwater extraction, and water usage increased from 1.534 billion cubic meters to 3.47 billion cubic meters from 1975 to 2000 [70].

The present research covers a total area of 107,886.37 square kilometers, which includes the 16 districts that constitute Punjab's five major divisions, as indicated in Table 1. The map of the research areas in the province is shown in Figure 1.

Table 1. List of Districts Included in the Study Area.

Divisions	Districts	Latitude	Longitude
Rawalpindi	Jhelum	32°56′25.9728″	73°43′39.4716″
	Attock	33°46′4.9836″	72°21′38.5308″
	Chakwal	32°55′51.9564″	72°51′18.3096″
Lahore	Sheikhupura	31°42′59.9796″	73°59′6.0828″
	Nankana Sahib	31°26′51″	73°41′49.99″
Faisalabad	Chiniot	31°43′12″	72°58′44″
	Toba Tek Singh	30°58′23.34″	72°28′27.74″
	Jhang	31°16′17.54″	72°19′42.31″
Sargodha	Khushab	32°17′43.93″	72°20′55.94″
	Mianwali	32°34′26″	71°31′35″
	Bhakkar	31°37′30.90″	71°03′56.66″
Gujranwala	Gujrat	34°17′0″	72°10′0″
	Hafizabad	32°4′18.1092″	73°41′8.6280″
	M.D Bahu Uddin	32°35′0.2″	73°29′3.52″
	Narowal	32°12′60.00″	74°56′59.99″
	Sialkot	32°29′33.65″	74°31′52.82″

2.2. Overall Research Framework

As shown in Figure 2, the research methodology starts with the basic stage of data collection from different sites. For this study, samples collected from the water and sanitation agency (WASA) and urban units were evaluated for the presence of physicochemical parameters including pH, chloride (Cl^-), fluoride(F^-), iron (Fe^{-2}), nitrate (${NO_3}^{-1}$), nitrite (NO_2), arsenic (As), total hardness, bicarbonate (${HCO_3}^-$), calcium (Ca^{+2}), magnesium (Mg^{+2}), color, taste, turbidity, total dissolved solids (TDS) and microbiological parameters including total Coliforms, fecal coliforms, and Escherichia coli. Irrigation parameters including electrical conductivity (EC), residual sodium carbonates (RSC), and sodium adsorption ratio (SAR) were gathered from the Punjab irrigation department. In addition to these parameters, depth-to-water-table data were also compiled. Daily rainfall data for the studied year were also collected from the Pakistan Meteorological Department (PMD). Annual rainfall for all the divisions was used to calculate the index value. After collecting the required data, the analysis of data is initiated to achieve the objectives. To compute the water quality index for groundwater data, a four-step protocol is followed: (i) Selection of the parameters, (ii) transformation to sub-indices, (iii) establishment of the weights, and (iv) aggregation of sub-indices to the final index value, in which, the Analytical Hierarchy Process is used for the determination of the weights for the selected parameters. In the Analytical Hierarchy Process (AHP), the elementary component is pairwise comparisons of the selected alternatives (water quality parameters). To generate the pairwise matrix, the researcher must establish the priorities for their main criteria (drinking, irrigation) by setting them side-by-side based on their relative importance using the Satty scale, and the index is classified into different classes. After computing the indices for drinking as well as irrigation purposes, the values are interpolated onto the maps in order to split the study area into different zones. By identifying the quality zones, different strategies can be proposed for the mitigation of groundwater quality and to maintain the overall conditions of groundwater for a sustainable future.

2.3. Data Collection

Data for assessing and evaluating water quality for the year 2018 were collected from different sites in Punjab Province from the concerned departments. The data collected for the research consisted of physicochemical parameters, groundwater level data, and climatic data from the Pakistan Environmental Protection Agency, the Punjab Irrigation Department, and the Pakistan Meteorological Department, respectively.

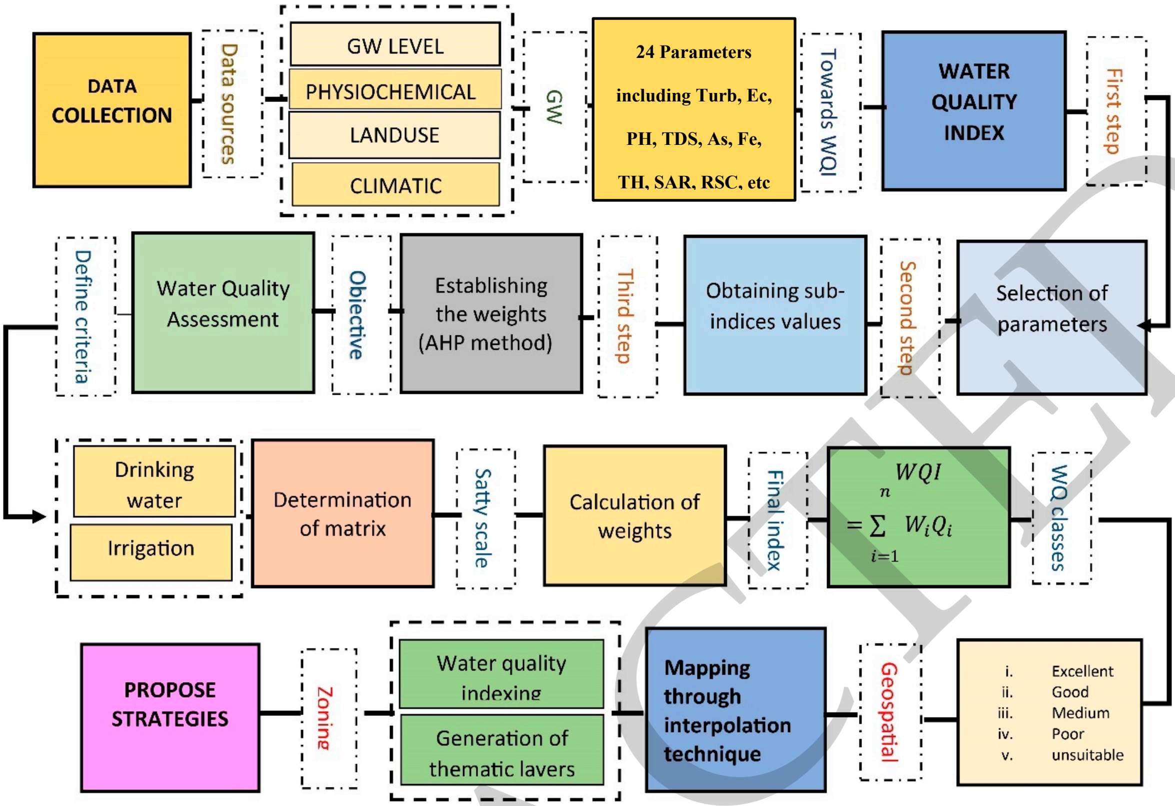

Figure 2. Methodological Framework of Research.

Land Use

Remotely sensed data of sentinel-2A MSI (multispectral instrument) images captured in 2018 were collected from the USGS. These images were interpreted and land types were identified using the normalized difference vegetation index (*NDVI*). The Normalized Difference Vegetation Index (*NDVI*) calculates vegetation abundance and health by measuring the difference between near-infrared (*NIR*) and red light reflected by vegetation. It is derived from satellite imagery and calculated as $(NIR - Red)/(NIR + Red)$, producing values between −1 and 1. Higher *NDVI* values indicate healthier, denser vegetation, while lower values suggest sparse or non-existent vegetation. *NDVI* is widely used in agriculture, forestry, and environmental monitoring to assess vegetation growth, health, and land use changes over time [71].

$$NDVI = \frac{NIR - Red}{NIR + Red} \tag{1}$$

2.4. Data Analysis

Water Quality Indices

The Water Quality Index (*WQI*) serves as a unified, simplified measure aggregating various water parameters into a single numerical value, offering an effective and straightforward assessment of water quality. This index assesses parameter importance, establishes statistical correlations between parameter concentrations and the index, correlates different aspects of water quality, and classifies quality levels from excellent to unsuitable. In this study, the *WQI* for groundwater considers physical, chemical, heavy metal, and microbiological parameters, condensing extensive data into a singular value, and facilitating a straightforward interpretation of water quality status. While *WQI*s share a common structure, their development was aimed primarily at streamlining water quality assessment and facilitating easier comprehension of monitoring data. These aims can range from broad water quality assessments to specific applications. Many indices were devised following the method of Horton [43], but despite these efforts, a widely accepted way of producing water quality indices has yet to be developed. The *WQI* literature, as well as the specific region or country where the different indices were used, are discussed in this section. As outlined below, indices commonly use four phases to compute a *WQI* [72]: selection of the parameters, transformation to sub-indices, establishment of the weights, and aggregation of sub-indices to the final index value (Figure 3).

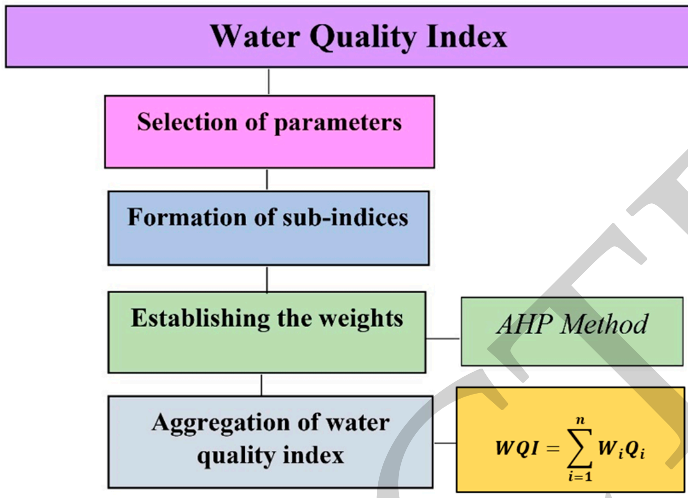

Figure 3. General outline of *WQI* computation.

2.5. Selection of the Parameters

For calculating the index, the selection of the parameters is the preliminary step. Those parameters (physical, chemical, microbiological, and heavy metals) that have a great influence on the water bodies are emphasized. Selecting parameters for water quality assessments is a meticulous process guided by multiple considerations, each contributing a crucial rationale to ensure a comprehensive evaluation. First, the review of the existing literature [73] serves as a cornerstone, offering insights into parameters that have historically influenced water quality. This step ensures alignment with established scientific indicators, drawing from recognized factors impacting water quality. Additionally, the availability of data [74] plays a pivotal role, as the feasibility of including certain parameters depends on their accessibility and reliability. Practical constraints might limit the inclusion of vital parameters if adequate data are unavailable. Another key consideration is the avoidance of parameter redundancy [75], ensuring that parameters selected for evaluation offer unique insights rather than duplicating information. Streamlining parameters minimizes unnecessary complexity, focusing on distinct aspects that collectively portray the overall water quality. Lastly, the parameters chosen should collectively reflect the comprehensive state of water quality [76], encompassing diverse facets such as physical, chemical, and biological aspects. This holistic approach aims to provide a nuanced understanding of the water body's condition, ensuring a thorough assessment that captures various dimensions of water quality.

2.6. Transformation to Sub-Indices

This phase focuses on standardizing water quality parameters, which initially come in various units, into a unified scale for aggregation. For instance, parameters like ammonia nitrogen might be measured in mg/L, while turbidity is assessed in NTU [72]. The aggregation process in most Water Quality Indices (*WQI*s) requires parameters to be on the same scale, necessitating normalization into sub-indices. This normalization step is essential to ensure the comparability and combinability of diverse parameters in the assessment.

The chosen parameters are categorized into positive and negative indicators based on their impact on water quality [77]. Positive indicators are those where higher values signify better water quality, while negative indicators indicate deteriorating water quality with higher values. Ideally, the favorable scenario involves higher values for positive indicators and lower values for negative ones. To standardize these parameters, positive indicators are normalized using Equation (2), while negative indicators utilize Equation (3). This normalization process ensures a consistent basis for comparison and evaluation across these different types of indicators.

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

For negative indicators,

$$R_i = 1 - \frac{x_i - x_{min}}{xmin_{max}} \tag{3}$$

where R_i represents the sub-index of study region I, x_i is the actual value of the indicator in region I, and x_{min}, and x_{max} indicate the minimum and maximum values in the data set, respectively.

2.7. Determination of the Weights

Based on the relative importance of the selected parameters, weights are assigned to the parameters as well as their influence on the final index value. Generally, equal or uneven weights can be assigned to the parameters. If all the index's parameters are of equal importance, they are assigned equal weights; however, if some of the selected parameters are comparatively more essential than others, unequal weights are applied.

Multi-Criteria Decision Analysis approaches are classified into two categories, multi-objective and multi-attribute methods, and they are both concerned with ways to combine several criteria into a single evaluation index [78]. In MCDA, each criterion is assigned a weight to reflect its true significance in the phenomena [79].

In the present study, the method adopted for assigning the weights is the Analytical Hierarchy Process.

2.8. Analytical Hierarchy Process

The Analytical Hierarchy Process (AHP) method is one of a Multi-Criteria Decision Analysis (MCDA) methodology and is based on a subjective approach in which weights are allocated by pairwise comparisons between various criteria derived through policies proposed by Satty et al. [80]. Satty created a powerful and useful tool for handling qualitative and quantitative multi-criteria aspects that play a role in decision-making. The general outline for the AHP method is shown in Figure 4.

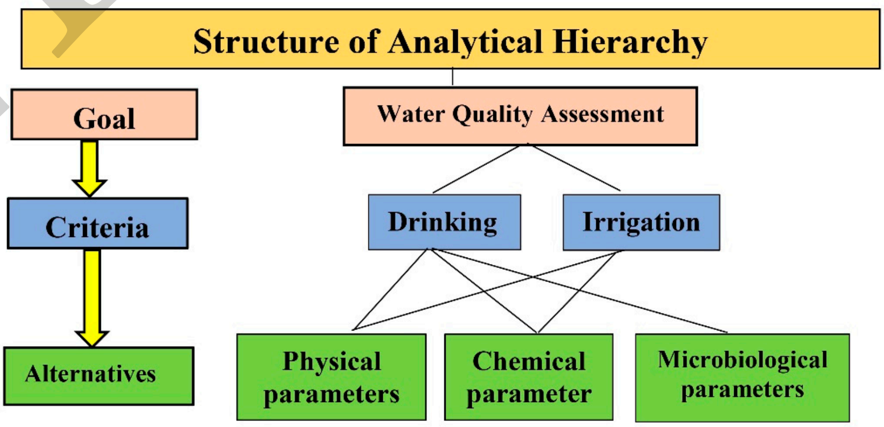

Figure 4. Structure of the Analytical Hierarchy Process.

The Analytical Hierarchy Process (AHP) consists of three stages, starting with the selection of a goal that is purely based on the problem related to the research objectives (water quality assessment), which depends on the criterion or criteria (drinking, irrigation), followed by the selection of alternatives (physical, chemical, heavy metals, microbiological parameters) [81].

2.9. Pairwise Comparisons of Alternatives

In the Analytical Hierarchy Process, the elementary component is pairwise comparisons of the selected alternatives (water quality parameters). To generate a pairwise matrix, the researcher must establish the priorities for their main criteria (drinking, irrigation) by setting them side-by-side based on their relative importance [82].

2.10. Preparation of the Questionnaire

The questionnaire was prepared using the well-known Satty scale, which ranges from 1–9 points. The Satty scale is highly recommended for use as a universally acceptable scale as it provides more and better options to establish the relative importance of parameters. Respondents are required to fill out the upper triangular component of the questionnaire's matrix. For this study, the structured questionnaire was distributed among researchers to prioritize the parameters (Table 2).

Table 2. 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

For each question, the respondent circles the response that best characterizes how they feel about the importance of water quality parameters for drinking purposes. A 1–9 point scale was used for the comparison [83].

2.11. Construct Pairwise Matrix

Judgments made by the respondents are 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 respondents. The parameters are denoted by 'P_1, $P_2 \ldots P_N$' and their weights by p_1, $p_2 \ldots p_N$ [80]. All of the matrix's diagonal elements are equal to one. As a result, the lower triangular component values were calculated automatically from the upper triangular component of the matrices' answers (Table 3).

Table 3. The pairwise matrix used in AHP.

	P_1	**P_2**		**P_N**
P_1	P_1/p_1	P_1/p_2	...	P_1/p_N
P_2	P_2/p_1	P_2/p_N	...	P_2/p_N
...	...	...		...
P_N	P_N/p_1	P_N/p_2	...	P_N/p_N

2.12. Weight Calculation (by Eigenvector)

The weights are elicited in general by using matrix algebra to find the primary eigenvector $w = (w_1, w_2, w_N)$ from matrix P where $w_i > 0$

$$\sum_{i=1}^{N} w_i = 1 \tag{4}$$

The primary eigenvector for $w_i = 1$ when a matrix is normalized becomes a priority vector for that matrix (i.e., weights) [83].

According to Satty [83], the primary eigenvector of P is the desired eigenvector. The following can be used to calculate the priority vector w.

$$Aw = \Lambda\ Max\ (w) \tag{5}$$

where Λ *Max* is the matrix A's biggest eigenvalue and w is the corresponding eigenvector. This strategy is known as the technique of eigenvalues [84]. The eigenvalue method is a technique for calculating eigenvalues. The weights of individual parameters/groupings of parameters were then estimated across all levels of the hierarchy.

2.13. Index Calculation

In this stage, the sub-indices are aggregated using mathematical procedures. These calculations generate a sub-index value for the assigned weights in the specified parameters, resulting in a total water quality status, which is commonly expressed as a single number. Their implementation is governed by the needed level of accuracy as well as whether the weight parameters are described unequally or evenly. Depending on whether the index comprises aggregated sub-indices, the aggregation procedure can be done in stages. For the sub-indices, there are four typical aggregation methods: additive (arithmetic), multiplicative (geometric), minimal operator, and the harmonic mean of squares.

For the determination of the water quality index, the additive method was applied. This method does not require a comparison with the standard or thresholds specified by the WHO. The final index value was computed by the following equation [85].

$$WQI = \sum_{i=1}^{In} W_i Q_i \tag{6}$$

where n = represents the number of parameters selected, W_i = weight of individual parameters, and Q_i = measured value or laboratory experimental value of parameters.

2.14. Ground Water Quality Assessment for Drinking Purpose

Moving from the Water Quality Index (*WQI*) framework, the assessment pivoted towards a specialized analysis tailored for evaluating groundwater suitability for drinking. This focused evaluation delved into specific parameters crucial for assessing the adequacy of water for human consumption. To compute the index for drinking purposes, four steps were followed. First, 21 groundwater quality parameters (pH, chloride (Cl^-), fluoride (F^-), iron (Fe^{-2}), nitrate ($NO_3{}^{-1}$), nitrite (NO_2), Arsenic (As), total hardness, bicarbonate ($HCO_3{}^-$), calcium (Ca^{+2}), magnesium (Mg^{+2}), color, taste, turbidity, total dissolved solids (TDS), total coliforms, fecal coliforms, Escherichia coli, water levels, precipitation) were selected. Weights for these parameters were assigned using the Analytical Hierarchy Process (AHP) according to their relative importance in the groundwater quality status and the final index was computed by using the aforementioned formulae. Using the computed indices, the groundwater quality index was classified into five classes (excellent, good, medium, bad, and very bad) [86]. Leveraging ArcGIS, a detailed zoning map was crafted to delineate the suitability of groundwater for drinking purposes. ArcGIS played a crucial role in spatially mapping [87–93] and categorizing groundwater quality within the study area, facilitating the identification of specific units primarily based on their groundwater suitability for drinking purposes. This geospatial tool enabled a visual representation of varying water quality, aiding in the identification and classification of areas where groundwater is suitable for drinking within the research field (Figure 5).

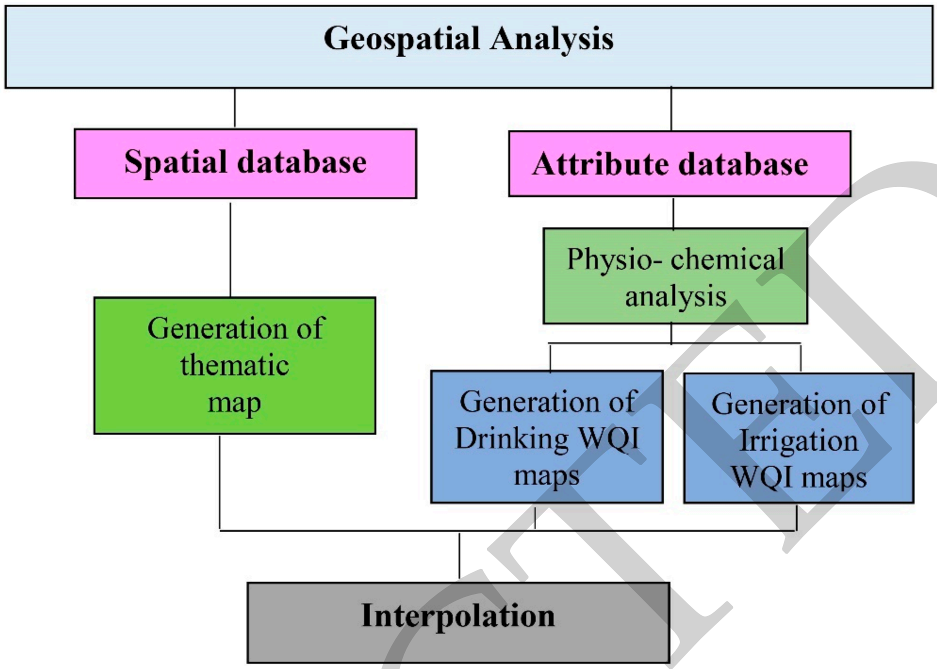

Figure 5. Geospatial analysis of Water Quality Indices.

2.15. Strategies for the Improvement of Groundwater Quality

Groundwater contamination presents a pressing concern not only within Punjab Province but throughout Pakistan. While prevention at the source remains crucial, immediate action becomes imperative once groundwater is polluted. Strategies involve treating water to lower chemical concentrations below WHO limits and employing measures to prevent chemical contamination. New insights for enhancing groundwater quality may encompass implementing advanced treatment technologies, such as nanofiltration or advanced oxidation processes, aiming to achieve stringent contaminant removal. Additionally, adopting sustainable agricultural practices, reducing the use of harmful pesticides and fertilizers, and implementing stringent industrial discharge regulations can significantly contribute to mitigating groundwater pollution and improving its overall quality.

3. Results and Discussion

This research work included the evaluation of groundwater by spatial variations in selected parameters and the computing of water quality indices. The following results were obtained from the research.

3.1. Physicochemical Parameters

The present study examines the different physical and chemical parameters for assessing groundwater quality.

3.1.1. pH

pH signifies the concentration of hydrogen ions in logarithmic units. The pH scale ranges from 0–14, in which 0–7 represents an acidic and 7–14 an alkaline solution, while 7 is neutral pH. According to WHO standards, the acceptable range of pH in water is 6.5–8.5. As shown in Figure 6, the annual pH range recorded in the different divisions in the study area was: 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. A slightly alkaline pH is observed in the Sheikhupura district of the Lahore division, which might be due to the industries working there.

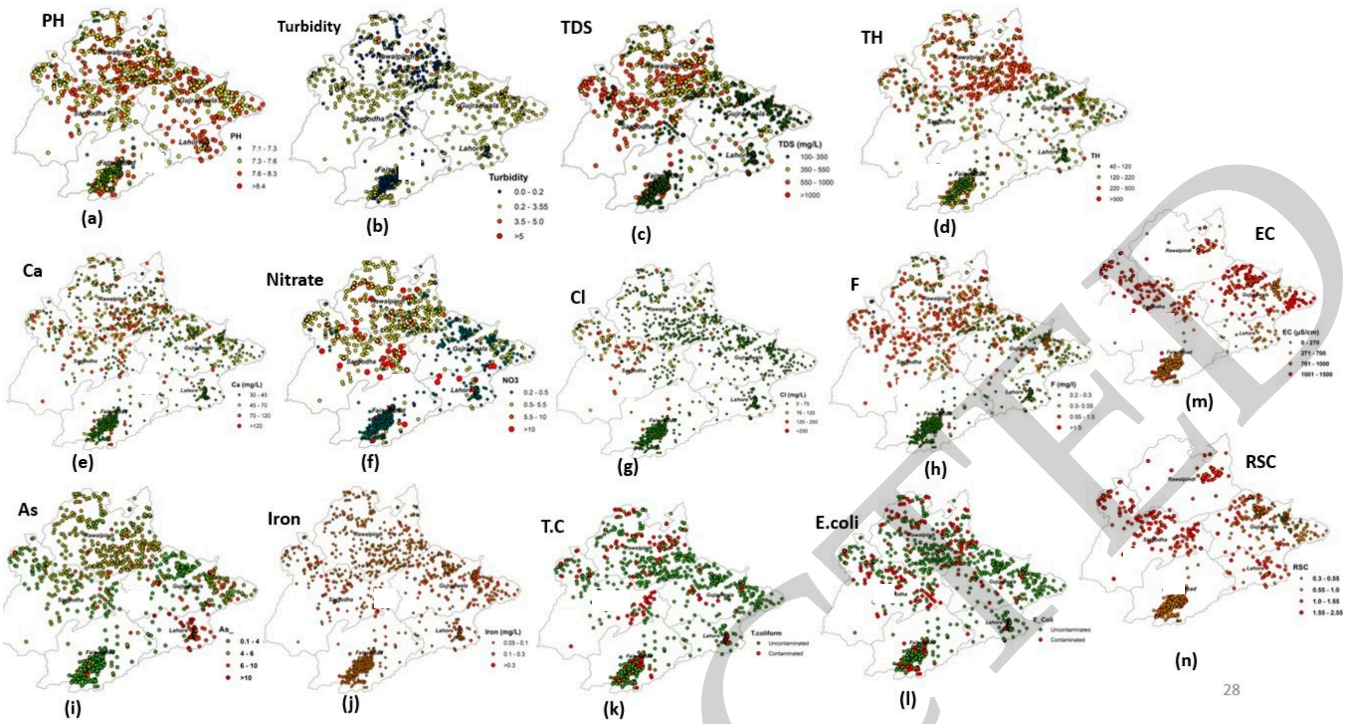

Figure 6. Spatial Variations in Physicochemical Parameters.

3.1.2. Turbidity

Turbidity is defined as the optical clarity of the water. Turbidity is mainly caused by the presence of suspended particles, which can be organic or inorganic. The source of the turbidity is harmless sediments (mostly clay soils); however, if hazardous contaminants become attached to them, they would harm the environment as well as health [94]. The measurement of turbidity is considered a priority indicator over other physical properties in various fields including wastewater management, water quality assessment (drinking, irrigation), planning, and ecological studies. According to the WHO, water turbidity must be no greater than 5 NTU. The results of this study show that, within the study area, the turbidity ranged from 2 NTU to 9 NTU. As shown in Figure 6, the highest values were observed in Sargodha (6.9 NTU) and Rawalpindi (5.2 NTU). This clearly shows that some areas of the study area required treatment that includes a sedimentation process to remove turbidity.

3.1.3. Total Dissolved Solids (TDS)

The total dissolved solids (TDS) indicates the soluble amount of inorganic salts. Generally, TDS quantifies the minerals present in the water. Elevated levels of TDS not only alter the taste but also enhance the hardness of the water [95]. The total dissolved solids increase due to the presence of different salts, including chloride (Cl^{-1}), total hardness, bicarbonate (HCO_3^-), calcium (Ca^{+2}), and magnesium (Mg^{+2}).

According to the WHO, TDS levels in drinking water should not exceed the acceptable limit of 1000 mg/L. Our results show that, within the study area, TDS ranged from 75–1350 mg/L. As shown in Figure 6, the highest values were observed in Sargodha (300–1350 mg/L) and Rawalpindi (104–1257 mg/L), while some parts of Faisalabad and Lahore exceeded the permissible limits. This is due to underground rock–water interaction.

3.1.4. Total Hardness

Total hardness depends on the concentration of calcium (Ca^{+2}), and magnesium (Mg^{+2}). The hardness of water is not considered pollution if it is only due to carbonates causing temporary hardness. However, when combined with bicarbonates, this leads to permanent hardness [96]. Water that has very high hardness is not suitable for drinking purposes. Hardness in water causes pipe blockages and an alteration in taste, and can even lead to various diseases including cardiovascular disease [97]. As shown in Figure 6, Sargodha had the highest number of samples of high hardness, with values ranging from 110 mg/L to 669 mg/L.

3.1.5. Calcium

Calcium is the fifth most abundant element found in water. The main sources of calcium are gypsum and calcite found in sedimentary rocks [98]. The main sources of calcium are rock–water interactions and contamination from industrial and domestic wastes [99].

Calcium ions were the major hardness-causing agent identified in the study, with values in the study area ranging from 12 mg/L to 160 mg/L. As shown in Figure 6, the areas with the highest values are Sargodha (166 mg/L) and (Rawalpindi) 114 mg/L.

3.1.6. Magnesium

Magnesium is the most common element found in the earth's crust and all available sources contribute to the hardness of water. A high concentration of this ion makes the water unpalatable [99].

According to the WHO, the acceptable limit of magnesium in drinking is 75 mg/L. The results from the study area show that the concentration of magnesium ranged from 8 mg/L to 110 mg/L, with Sargodha (101 mg/L) and Rawalpindi (98 mg/L) showing the highest values, as shown in Figure 6.

3.1.7. Nitrate

Nitrate for the environment is a less serious issue if present within the permissible limits; however, if the nitrate concentration exceeds the limits, in association with other factors, this leads to eutrophication [99]. The main sources of nitrate contamination are the excessive use of nitrogen-based fertilizers, domestic effluents, and leaks from sewage systems [100].

According to the WHO, nitrate levels should not exceed 10 mg/L; however, in the study area, overall, 6% of samples exceeded the limits set by WHO. As shown in Figure 6, over the whole study area, nitrate levels ranged from 2 mg/L to 18 mg/L.

3.1.8. Chloride

Chloride is present in relatively small amounts in water naturally [101]; however, contamination from industrial and sewage effluents, leachate, and sedimentary rock dissolution can lead to a high concentration of chloride, which alters the taste of the water. Although generally, it does not have adverse effects, it can adversely affect vulnerable people [102].

The WHO admissible level of chloride in drinkable water is 250 mg/L. The results from the study show that chloride levels within the study area ranged from 18 mg/L to 350 mg/L, and, as shown in Figure 6, Sargodha had the highest levels (350 mg/L).

3.1.9. Fluoride

Fluoride is a natural contaminant that occurs due to the weathering of rocks followed by percolation into the groundwater. Non-natural sources, including pollution from coal-burning industries released into the atmosphere, contribute to groundwater contamination [103].

According to the WHO, fluoride levels should not exceed 1.5 mg/L. Our results show that, within the study area, levels ranged from 0.1 mg/L to 2.08 mg/L, with, as shown in Figure 6, some samples in Sarghoda exceeding the WHO limit.

3.2. Heavy Metals

3.2.1. Arsenic

Arsenic is categorized as a hazardous metal. Water contamination due to arsenic is an issue of concern, not only in Pakistan but all over the globe. Arsenic can enter the supply due to anthropogenic activities, mainly the dumping of industrial effluents containing toxic metals directly into water channels, and naturally, due to natural deposits of the metal [104,105].

Heavy metal contamination emerged as a problem at the dawn of the Industrialization Era. According to the WHO, arsenic levels must not exceed 10 mg/L. In our study, the highest arsenic levels within the study area were observed in the Lahore division, and, as shown in Figure 6, some areas of Sargodha and Faisalabad have heavy metal pollution.

3.2.2. Iron

Iron is found naturally and the concentration of iron is higher in groundwater than in surface water. The sources of groundwater contamination are the weathering of rocks bearing the metal, untreated industrial effluent, and leachate from landfills [106–108]. According to the WHO, iron levels should not exceed 0.3 mg/L. As shown in Figure 6, some samples from Sarghoda exceed the permissible limit, showing a range of 0.2 mg/L–9 mg/L.

3.3. Microbiological

Drinking water contaminated with pathogens poses a serious threat to human health as consuming pathogen-contaminated water causes several diseases including cholera, typhoid, and fevers, as well as hepatitis and other chronic diseases [109]. Waterborne diseases are the result of the consumption of fecally contaminated water. For water quality assessment, microbial contamination is considered one of the most important parameters [110].

3.3.1. Total Coliforms

Coliforms refer to the type of bacteria found in the environment that are Gram-negative and rod-shaped but are not spore-forming. In water quality monitoring, the different types of bacteria (total coliforms, fecal coliforms) are considered according to the level of risk they represent [111]. Generally, the levels of total coliforms present in a water body indicate how clean the water supply is. According to the standards set by the WHO for drinking, no total coliform colonies must be detectable in any 100 mL sample of the water body [112]. Our analysis showed that the results for total coliforms are similar for all parts of the study area, as shown in Figure 6.

The findings are strongly supported by the results of other studies [107,113,114] for different cities of Punjab. The major sources of microbial contamination across the study area are municipal effluents, improper solid waste management, and open septic tanks [14,115].

3.3.2. *E. coli*

E. coli is the major indicator of fecal coliform contamination in water compared to other members of the fecal group. The monitoring and assessment of water quality primarily relies on the monitoring and assessment of *E. coli* levels. Some strains of this species can be harmful while others are harmless [116]. According to the standards set by the WHO for drinking, the total number of coliform colonies must be detectable in any 100 mL sample of a water body [94]. Our analysis showed that *E. coli* levels are similar for all parts of the study area, as shown in Figure 6. These findings are supported by the results of other studies for different cities in Punjab Province.

The major sources of fecal contamination, in particular for *E. coli*, are waste effluents, leaks from sewerage systems, and the improper laying of pipelines. Waste effluents are responsible for most microbial contamination, not only in surface water but also in groundwater. The major recharging sources of groundwater include rivers, canals, and streams.

These become polluted with waste effluent and then percolate into the groundwater and contaminate it with microbes. The Ravi River and Lahore Canal in Lahore, and Nullah Lai in Rawalpindi, are mainly responsible for the observed groundwater pollution [117,118].

3.4. Irrigation Parameters

Irrigation mainly relies on the availability of the minerals found in groundwater and many factors contribute to the ease of access to these minerals. The important parameters in assessing this availability are electrical conductivity (EC), sodium adsorption ratio (SAR), and residual sodium carbonate (RSC).

3.4.1. Electrical Conductivity (EC)

The electrical conductivity (EC) of water is measured in terms of the amount of soluble salts in mg/L and is a measure of the salinity hazard. Some physical properties of the water such as as odor and color are associated with EC levels [119]. In groundwater, elevated levels of electrical conductivity are mainly due to the presence of sodium bicarbonate and carbonate ions [120]. According to the standards, electrical conductivity levels should not exceed 1500 mg/L, and for good crop yields, should approach 750 mg/L [121]. The results of the study area show that electric conductivity levels ranged from 277 mg/L to 5717 mg/L within the study area. As shown in Figure 6, the highest values were observed in Sargodha and some parts of Lahore and Rawalpindi. The high electrical conductivity levels are due to contamination from industrial effluents and the excessive use of fertilizers [122].

3.4.2. Sodium Adsorption Ratio (SAR)

The sodium adsorption ratio (SAR) is representative of the sodium (Na^{+})-to-calcium (Ca^{+2}) ratio. The SAR typically indicates the sodium hazard [123].

A suitable SAR value for irrigated water is 5 and SAR values for the groundwater within the study area ranged from 0.22 to 5.8 [121]. The highest value observed was within Sargodha (5.8).

3.4.3. Residual Sodium Carbonate (RSC)

The bicarbonate content in water is measured in terms of residual sodium carbonate. A high concentration of bicarbonate increases the tendency of precipitation into the soil, thus affecting crop yields [124]. According to the standards, the RSC should not exceed 2.5, and for good crop yields should be less than 1.25.

RSC values for the groundwater within the study area ranged from 0.31 to 4.3, with, as shown in Figure 6, the highest values being observed within Rawalpindi (4.3) and Sargodha (5.8).

3.4.4. Comparison of GW Parameters with International Standards

For water quality assessment, 1094 data points were analyzed in the study area. The data sets were then compared with World Health Organization (WHO) standards, as shown in Table 4. 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 province as a whole, while at the division level, Lahore had arsenic levels of 25% and microbial contamination levels of 31%. Most samples from Rawalpindi and Gujranwala exceeded the standards. In terms of microbial contamination, Sargodha was the most polluted zone in the study area. The observed microbial contamination levels (19%), alongside the levels of heavy metals (9%), nitrates (10%), and hardness (12%) might be due to the use of open septic tanks, poorly managed sewerage systems along the water supply lines, and improper dumping of waste. The prevalence of microbial contaminants exceeding WHO thresholds in the study area, particularly total coliforms and *E. coli*, underscores the significance of microbiological pollution in groundwater. Specific divisions like Lahore, Rawalpindi, and Gujranwala demonstrate heightened levels of arsenic and microbial contamination, possibly linked to local industrial or urban activities. The noteworthy challenges observed in Sargodha, with elevated levels of microbial contaminants, heavy metals, nitrates, and hardness, suggest potential issues stemming from inadequate waste disposal practices and poorly managed sanitation systems. Addressing these localized issues, such as improving waste management and upgrading sewage systems, is crucial for the mitigation of groundwater contamination in these regions.

Table 4. Comparison of GW parameters with International Standards.

Parameters	WHO	Percentage of Samples Exceeding the Limit					
	Standards	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
T 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

3.4.5. Relative Proportions of Parameters

As shown in Figure 7, the groundwater quality parameters were categorized into different classes—physicochemical, ions and metals (further into the anions, cations), heavy metals (Arsenic, Iron), and microbiology (total coliforms, fecal coliforms, *E. coli*)—to permit a relative assessment.

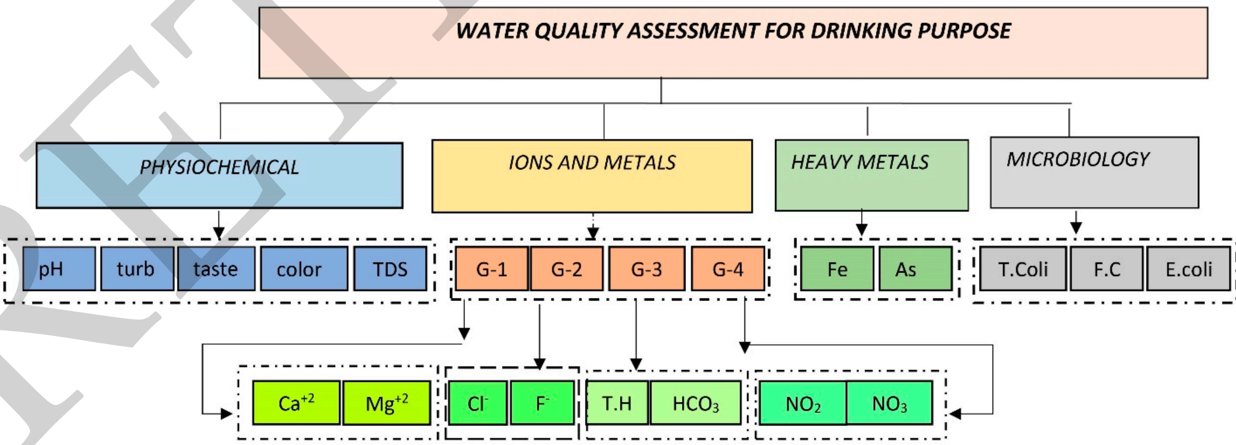

Figure 7. Pairs of Different Groundwater Quality Parameters.

In the study area, in terms of physicochemical parameters (Figure 8a), the dominant parameter is pH. In terms of ions and metals (Figure 8b), the relative proportions of the parameters are calcium 28%, fluoride 21%, and Nitrate 14%. In terms of heavy metals (Figure 8c), the proportions are arsenic 63% and iron 37%. In terms of microbial parameters (Figure 8d), the proportions are *E. coli* 53%, total coliforms 35%, and fecal coliforms 12%.

The dominance of pH in terms of physicochemical parameters highlights its significant influence on water quality within the study area. In terms of ions and metals, calcium, fluoride, and nitrate demonstrate considerable proportions, signifying their impact on groundwater composition. Heavy metals, particularly arsenic and iron, exhibit a notable dominance, suggesting a concerning prevalence of these contaminants. In terms of microbial parameters, *E. coli* dominates, followed by total coliforms and fecal coliforms, indicating a substantial presence of these microorganisms in the sampled water sources. These findings underscore the multifaceted nature of water quality issues, emphasizing the need for comprehensive management strategies targeting a range of parameters to ensure safe and clean groundwater.

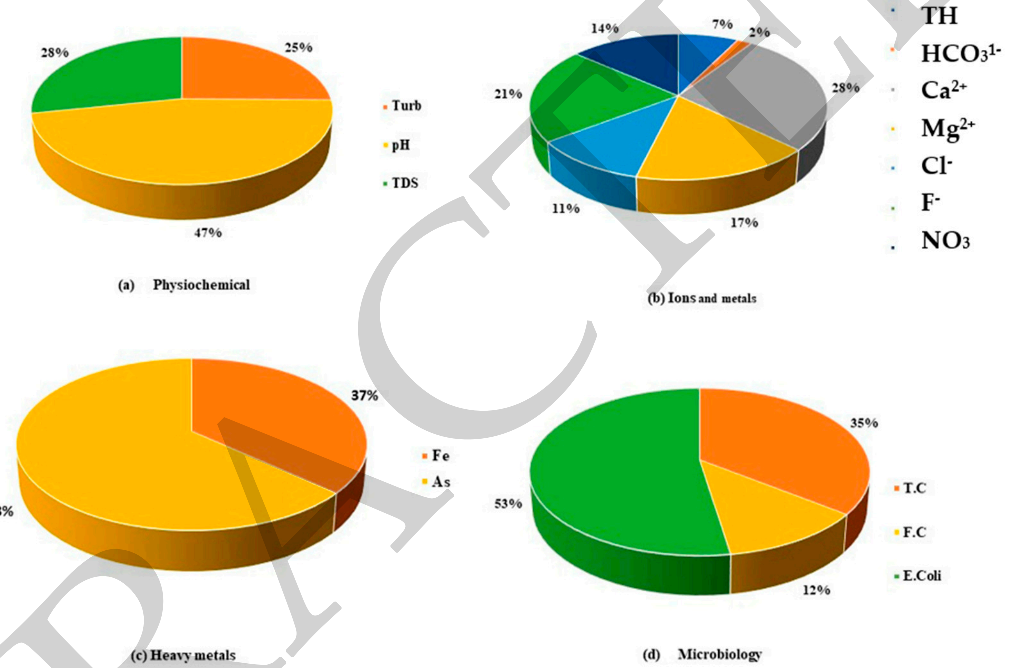

Figure 8. (**a**–**d**) Relative Proportion of Different Parameters.

3.5. Water Quality Index

The water quality index was calculated for different groundwater quality parameters, followed by the normalization of these selected parameters. The selected parameters were categorized into positive and negative indicators, as shown in Table 5.

3.6. Determination of Weights

AHP Questionnaire

The AHP questionnaire prepared for the study was distributed to 25 individuals. All the questionnaires were returned on time, and the respondents' responses were tabulated into Excel sheets. Next, their responses were transported into matrices and the relative importance of the parameters for different criteria such as drinking and irrigation were noted. The responses were computed to calculate the weights of individual parameters. The majority of respondents gave greater weight to the levels of iron, TDS, fecal coliforms, arsenic, and total coliforms; however, some gave greater weight to the levels of nitrate, *E. coli*, and chloride. All other parameters were assigned broadly the same importance. The highest weights were assigned to the levels of heavy metals, likely because heavy metal contamination is increasing exponentially in urbanized areas.

Table 5. Selected indicators and AHP weights.

Criteria	Alternatives	Indicator		AHP Weight
		Positive	Negative	
Drinking	Taste			0.010
	Odor		√	0.010
	Color		√	0.010
	Turbidity		√	0.029
	pH		√	0.040
	TDS		√	0.057
	Total hardness		√	0.050
	HCO_3		√	0.053
	Ca		√	0.049
	Mg		√	0.046
	Cl		√	0.041
	F		√	0.045
	Iron		√	0.052
	NO_3		√	0.035
	NO_2		√	0.039
	As		√	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

3.7. Groundwater Quality Assessment for Drinking Purpose

A total of 21 groundwater quality parameters were used to compute the final index for drinking purposes using the Analytical Hierarchy Process. The water quality index was computed for five divisions of Punjab Province. Using the computed indices, the groundwater quality index was classified into five classes (excellent, good, medium, bad, and very bad) as shown in Table 6 [70].

Table 6. Range of Water Quality Index specified for drinking purposes.

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

The indices were evaluated for the five divisions. The values show that most areas (38.54%) fell within class IV, while only a very small area (11.53%) reached class II. In the study area, no area reached class I, the excellent category. As shown in Figure 9a, the highest values for the index (i.e., lowest water quality) were found in Sargodha (122.99), Lahore (122.925), and Rawalpindi (121.261) (Figure 9a,b). The distribution of index values across the divisions reveals a concerning trend in which a significant portion of the study area falls within class IV, indicating compromised groundwater quality. It is noteworthy that no part of the studied regions reached class I (excellent), signaling the absence of areas with optimal water quality. Sargodha, Lahore, and Rawalpindi show the highest index values (lowest water quality), surpassing the other divisions, suggesting more pronounced water quality issues in these regions. These findings underscore the urgency of implementing targeted interventions and stringent measures to improve groundwater quality, especially in areas exhibiting higher index values, to ensure access to safe and potable water resources for the communities residing in these regions.

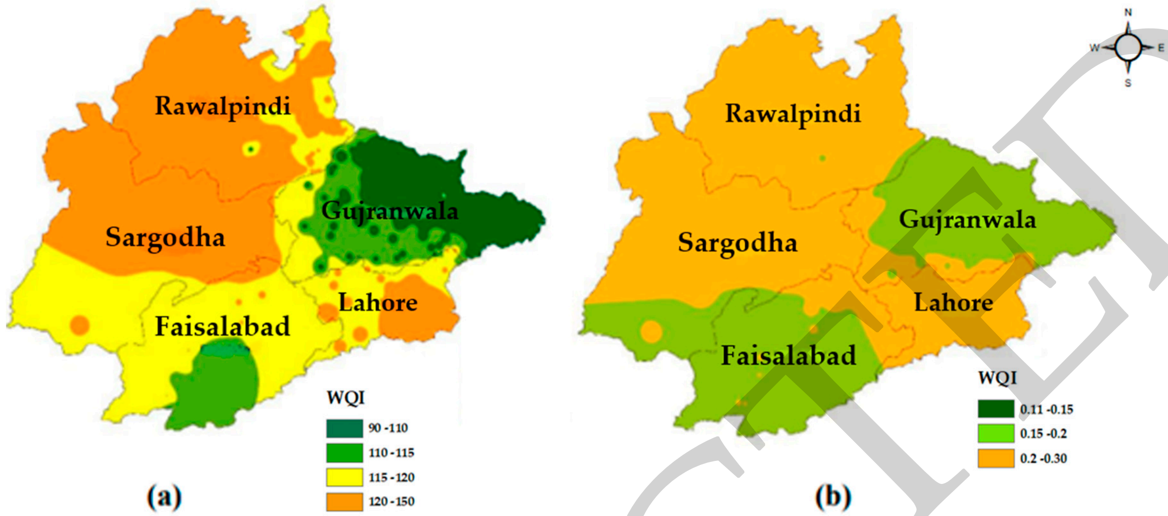

Figure 9. Water Quality Indices (**a**) *WQI* for Drinking, (**b**) *WQI* for Irrigation.

3.8. Ground Water Quality Assessment for Irritation Purposes

The *WQI* for irrigation was computed by using the irrigational parameters (EC, SAR, RSC). Using the computed indices, the groundwater quality index was classified into four classes (excellent, good, permissible, and unsuitable) [125] as shown in Table 7.

Table 7. Range of Water Quality Index specified for irrigation purposes.

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

The index value shows that most areas (69.18%) fell within class III, permissible, while the remaining areas (30.82%) fell within class II, good. As shown in Figure 9b, the highest index values (lowest water quality) were found for Rawalpindi (0.29), Lahore (0.28), and Sargodha (0.21). The predominance of the permissible category (class III) in the index distribution, encompassing a significant portion of the study area (69.18%), suggests a moderate level of groundwater quality. However, it is encouraging to note that about 30.82% of the region falls within the good category (class II), indicating relatively better water quality in those parts. Rawalpindi, Lahore, and Sargodha exhibited the highest index values (lowest water quality), implying areas with more pronounced water quality challenges within the study. These findings highlight the need for strategic interventions to enhance water quality across various divisions, particularly in regions where the index values signify greater issues, aiming to elevate the overall groundwater quality for improved public health and environmental wellbeing.

3.9. Impact of Urbanization and Industrialization on Water Quality

Unplanned urbanization and the conversion of agricultural land to industrial regions are two of the major causes of water quality deterioration [126]. Punjab's population is increasing exponentially. Between 1951 and 2017, the population of Punjab quadrupled from 20 million to 110.011 million [127]. The trend of migrating from rural areas to urban for an improved livelihood and a better quality of life leads to the overexploitation of resources; and, as shown in Figure 10, comparing the land use/land cover map of the study area with the water quality index map, it can be seen that groundwater quality index values are indeed higher in urbanized areas (Figure 10).

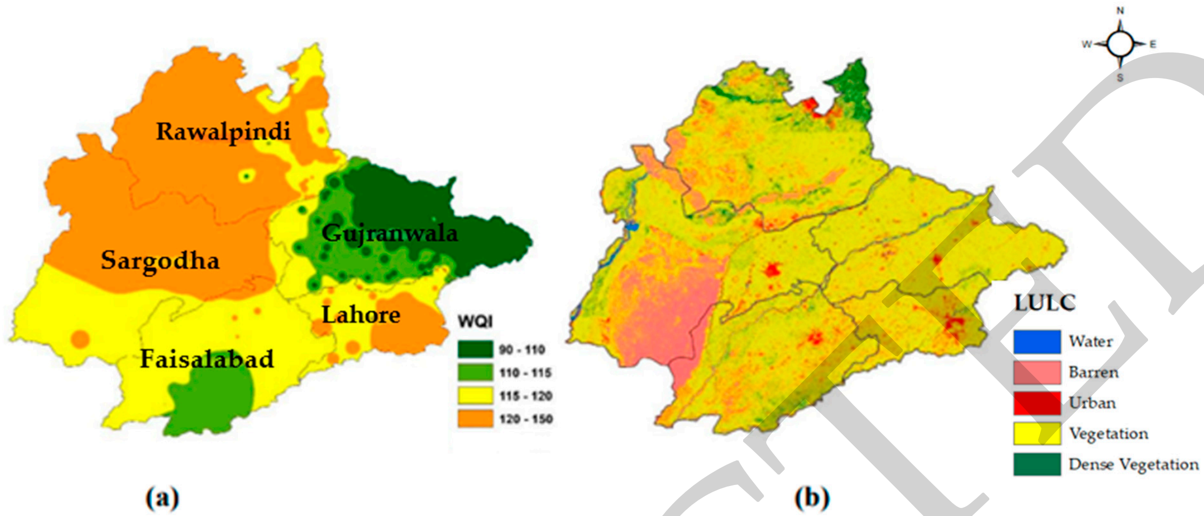

Figure 10. Comparison of water quality index map (**a**) with land use/land cover map (**b**).

Lahore is the second largest metropolitan city of Punjab and has more serious drinking water quality issues [93]. The water supply–demand chain is balanced by extracting the groundwater at depths of 120–200 m for domestic as well as industrial purposes [128]. A groundwater stress zone has been created because of groundwater overexploitation, while the recharging of resources is at a minimum. 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. In the previous 12–15 years, the city's size has nearly doubled. Due to land use changes, industrial growth, and continued expansion, the deterioration of groundwater quality is continuously observed. The depth to the aquifer around and under the city is ever-increasing, as can be seen from the increasing depth of wells required in the quest for relatively good quality water extraction [129]. In the case of Rawalpindi, since 2000, water needs have been solely met by the Rawal dam, the catchment area of which has been affected by the rapid 85% increase in urbanization [128]. The unavoidable stress placed on the available groundwater resources of increasing demand due to urban growth, a demand met in cities by using direct extraction of groundwater or by extracting the water from a diversified network of canals, will instantly instigate farmers to an equivalent overexploitation of groundwater resources. Under these circumstances, ever-increasing population growth leads to an increase in the domestic water demand affecting the agricultural sector's water schedules [68].

The lack of availability within the study area of good-quality groundwater is serious. There is a lack of proper management of the urbanized areas, monitoring of the resources, and implementation of the developed policies.

3.10. Development of the Mitigation Strategies

Water pollution describes the contamination of water sources including surface and groundwater [130]. The consumption of contaminated water leads to waterborne diseases. Sources of contamination can be summarized as municipal effluent, industrial effluent (heavy metals), and agricultural discharges (ions, salts, fertilizers). Groundwater contamination is a rising problem not only in Pakistan but all over the globe. The remediation of natural resources is crucial in the developing era to protect water resources. To formulate suitable strategies, a complete understanding of the physical, chemical, heavy metal, and microbiological parameters and the processes that affect the contaminant behavior are required. Mitigation approaches to restore the water to its natural condition can be achieved in two practical ways: (1) treat the water to reduce the concentration of chemical contamination below WHO limits, and (2) avoid chemical contamination by adopting different measures to control pollution.

3.10.1. Avoid Chemical Contamination by Adopting Different Measures to Control Pollution

The best way to control pollution is to control it at source. Control measures are devised based on the processes that are deteriorating the natural resources and the scenarios that can remediate the consequences of those hazardous activities (industrial effluents, agricultural run-off, and municipal and domestic wastes). As a first stage, the source of contamination should be identified at the point at which it occurs

Scenario-I (Variations in Microbiological Parameters)

Microbial contamination is a rising problem in the study area, as it was found to be the major contributor (27%) to groundwater pollution. There is a pressing need to control this pollutant as drinking water contamination with pathogens poses serious threats to human health and consuming pathogen-contaminated water causes several diseases including cholera, typhoid, and fevers, as well as hepatitis and other chronic diseases [131–138].

By considering the sources of microbial contamination, the microbes polluting groundwater can be controlled. The major sources of microbial contamination across the study area are municipal effluent, improper solid waste management, and open septic tanks [14,115,139]. In terms of fecal contamination, in particular, *E. coli* the sources are waste effluent, leaks from sewerage systems, and the improper laying of pipelines. Waste effluent is responsible for most of the microbial contamination not only of surface water but also of groundwater [132,140,141]. The Ravi River and Lahore Canel in Lahore and Nullah Lai in Rawalpindi are the main sources of groundwater pollution [118,132]. Possible control measures include:

i. Provide proper monitoring of the industry's effluent discharge points;
ii. Discharging wastewater only after a sequence of treatments;
iii. Equipping urban areas with treatment plants;
iv. Regular monitoring of the sewerage system;
v. Avoiding open septic tanks and their direct disposal in the open channels;
vi. Regularly monitoring the quality of pipelines;
vii. Laying water supply lines away from sewerage systems;
viii. Ensuring a large distance between landfills and domestic wells.

By adopting the measures above, and combining them with artificial recharging, three scenarios are devised to interpret the impact of these measures on the remediation of the groundwater in the contaminated regions of the study area. Figure 11a shows the impact on polluted areas of a 10% reduction in pollution with a 5% recharging of aquifers, Figure 11b the impact of a 20% reduction with 10% recharging, and Figure 11c the impact of a 30% reduction with 15% recharging. As can be seen, the latter treatment produces comparatively prominent results in Lahore, Rawalpindi, and Sargodha.

Scenario-II (Variations in Heavy Metal Parameters)

Heavy metal contamination is a prominent issue for the protection of groundwater in different zones of the study area including industrial, agricultural, and urbanized regions. The major contaminants within the study area are arsenic and iron, and the results show that Lahore, Faisalabad, and Sargodha are polluted with heavy metals.

Arsenic can enter the water supply due to anthropogenic activities, mainly the dumping of industrial effluents containing toxic metals directly into water channels, or due to natural processes affecting natural deposits of the metal [104,105]; while the sources of groundwater contamination due to iron are the weathering of rocks bearing the metal, untreated industrial effluent, and leachate from landfills [106–108]. Based on the sources of contamination identified by researchers, control measures should be devised and immediately implemented for the protection and minimization of groundwater resource pollution [142–144]. Possible control measures include:

I. Providing proper monitoring of the industry's effluent discharge points;
II. Restricting industry near any water supply line;
III. Only discharging wastewater after a sequence of treatments;
IV. Ensuring a large distance between landfills and domestic wells.

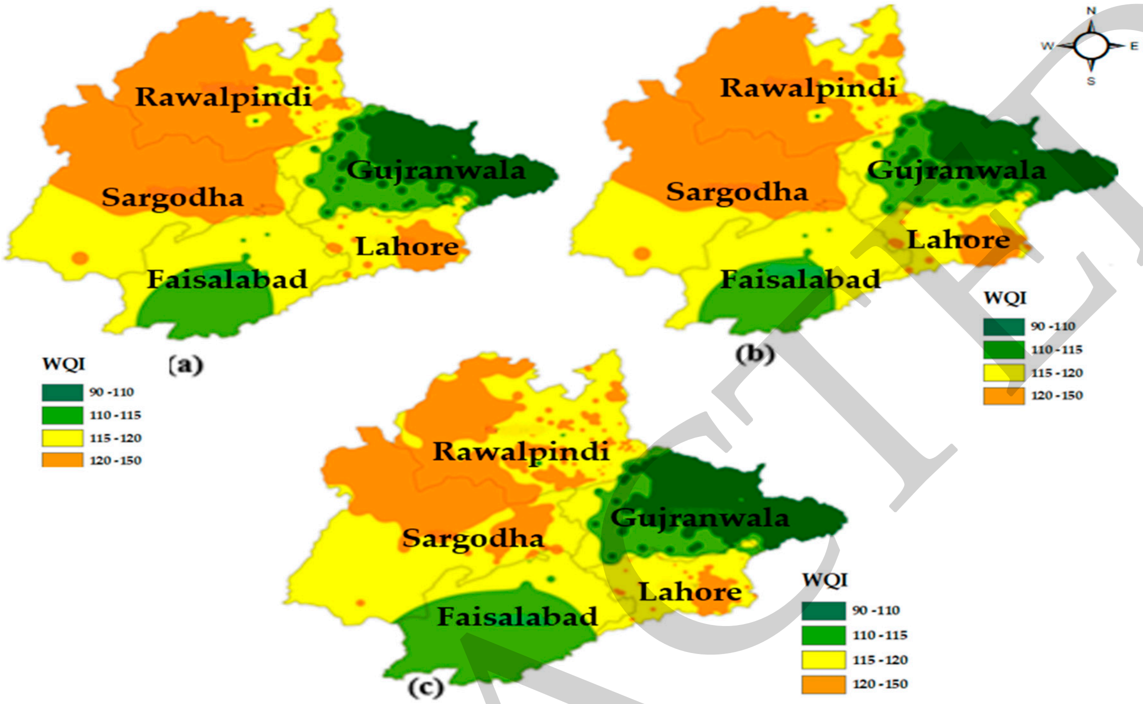

Figure 11. (**a**–**c**) Scenario-I (Variations in Microbiological Parameters).

By adopting these measures and combining them with artificial recharging, three scenarios are generated to interpret the impact of these measures on the remediation of the groundwater in the contaminated regions of the study area. Figure 12a shows the impact on the polluted areas of a 10% reduction in heavy metal contamination with a 5% recharging of the aquifers, Figure 12b the impact of a 20% reduction with 10% recharging, and Figure 12c the impact of a 30% reduction with 15% recharging. As can be seen, the latter treatment produces comparatively prominent results in Lahore, Rawalpindi, and Sargodha.

Scenario-III (Variations in Chemical Parameters)

The ions including cations and anions naturally present in groundwater determine the chemistry of the groundwater. These ions include cations such as calcium (Ca^{+2}) and magnesium (Mg^{+2}) and anions such as chloride (Cl^-), fluoride (F^-), nitrate ($NO_3{}^{-1}$), and nitrite (NO_2), total hardness (carbonates), and bicarbonate ($HCO_3{}^-$), and water quality is usually evaluated on the basis of these ions. The results of this study show that within the study area, the ions that are deteriorating groundwater quality in major parts of Sargodha, Lahore, and Rawalpindi include nitrate, fluoride, and hardness.

The main sources of the contamination are the excessive use of nitrogen-based fertilizers, domestic effluent, and leaks from sewage systems [100]. According to researchers, the major sources of fluoride are industrial waste and the leaching of rocks [64,103]. Based on the sources of ion contamination established by researchers, control measures should be devised and immediately implemented for the protection and minimization of groundwater resource pollution [145–147]. Possible control measures include:

I. Decreasing the use of nitrogen-based fertilizers by 10% to 20%;
II. Keeping drains isolated from the areas heavy in ions;
III. Providing highly contaminated areas with wastewater collection and treatment plants;
IV. Lining drainage channels to prevent seepage from drains into GW.

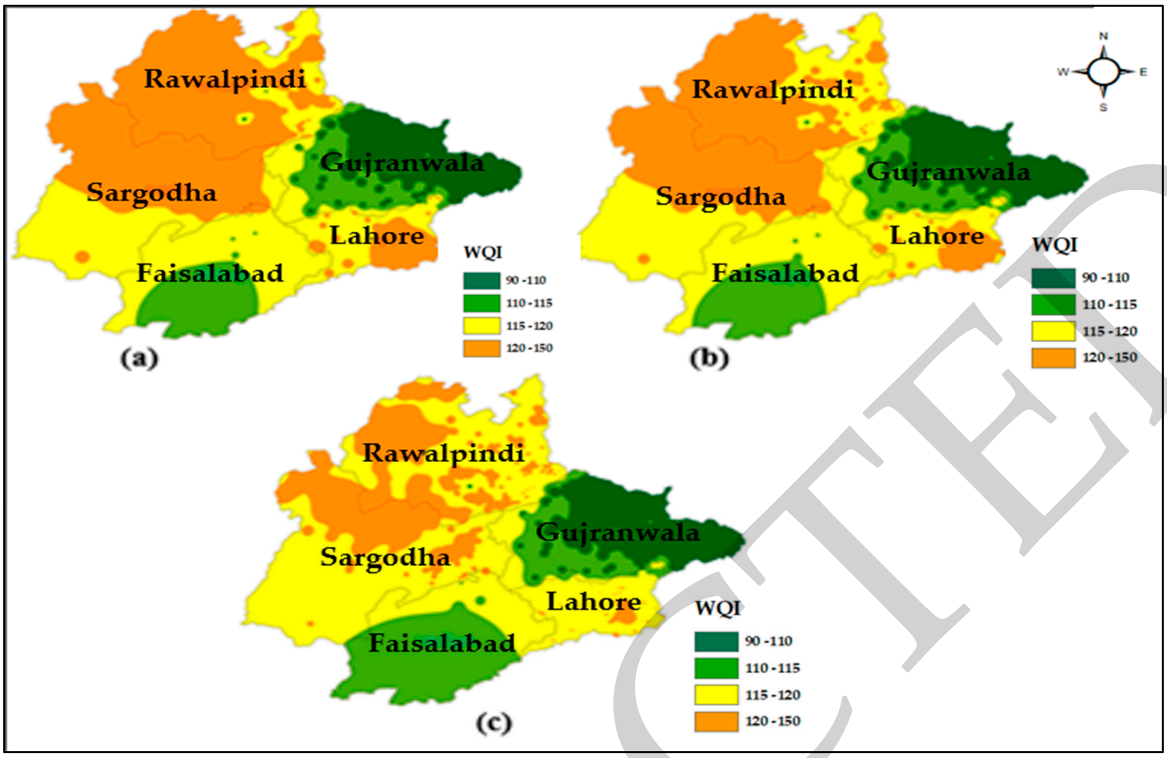

Figure 12. (**a**–**c**) Scenario-II (Variations in Heavy Metals).

By adopting these measures and combining them with artificial recharging, three scenarios are generated to interpret the impact on the contaminated regions within the study area of remediation of the groundwater. Figure 13a shows the impact of a 10% reduction in contamination with a 5% recharging of the aquifers, Figure 13b the impact of a 20% reduction with 10% recharging, and Figure 13c a 30% reduction with 15% recharging. As can be seen, the latter treatment produces comparatively prominent results in Lahore, Rawalpindi, and Sargodha.

3.10.2. Treatment of Water to Reduce the Levels of Chemical Contamination

The most primitive tool for controlling the pollution caused by different types of pollutants in wastewater treatment is treatment to reduce the levels of chemical contamination. This not only treats the wastewater but also improves the ecological aspects of the environment and conserves natural resources [148–150]. In Pakistan, wastewater treatment is struggling to keep up with the rate at which the problem of pollution is increasing. Domestic and fecal wastes are directly discharged into watercourses, internal septic tanks, and open fields. While a few cities, for example, Karachi and Islamabad, have implanted wastewater treatment plants (biological) for municipal waste, municipal wastewater is usually not treated [151–153]. The pollution caused by industrial effluent is the main problem and is still uncontrolled.

After control at the source, the next challenge is the removal of the contaminants. Different scenarios are generated based on the water treatment approaches taking note of the literature, as shown in Table 8, for the major pollutants (arsenic, microbiological contamination, nitrate). The efficiencies of these scenarios as well as their impact on the final index of each polluted region of the study area are then evaluated.

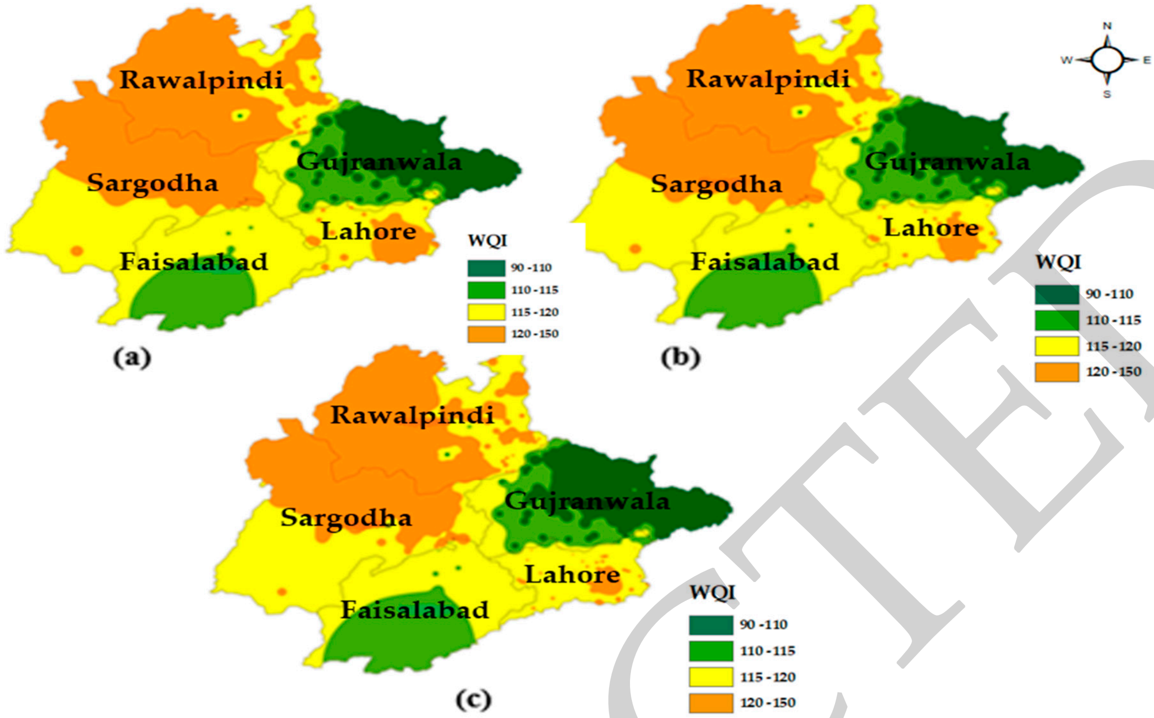

Figure 13. (**a**–**c**) Scenario-III (Variations in Chemical Parameters).

Table 8. Wastewater treatment processes.

Process	Parameter	Percentage	Source
Primary treatment	TDS Bacterial loadings	40–60% 40–60%	Al-Rekabi et al. [133] Zhou et al. [134]
Secondary treatment	TDS Bacterial loadings Hardness	65–80% 80–90% 45–55%	Al-Rekabi et al., Zhou et al., Monteiro et al. [133–135]
Tertiary treatment	Arsenic Nitrate	>95% 75–86%	Awual et al. [136] Valero et al. [137] Seenivasagan et al. [138]

Scenario-I (Primary Treatment)

In scenario I, the treatment of the wastewater in the primary stage is evaluated. As Figure 14 shows, the primary treatment is only efficient for removing the total dissolved solids (TDS) and bacterial loading. Three stages with different levels of treatment, as shown in Table 9, are established. Figure 14a shows the results with a 40% reduction in the total dissolved solids (TDS) and bacterial loadings by wastewater treatment, Figure 14b the results with a 50% reduction in the total dissolved solids (TDS) and bacterial loadings, and Figure 14c a reduction in both pollutants by 60%. The latter treatment produces comparable results in Lahore, Sargodha, and some areas of Rawalpindi. The impact of these three treatments on the computed indices is shown in Table 9. The results demonstrate the moderate efficacy of primary wastewater treatment in reducing TDS and bacterial loading, showcasing its initial impact on water quality improvement. However, the relatively limited reduction in pollutants, especially in highly polluted zones like Lahore and Sargodha, underscores the necessity of more advanced treatment stages for substantial environmental management progress. Incorporating these findings into environmental strategies highlights the need for comprehensive and multistage treatment approaches to effectively address groundwater pollution and ensure sustainable environmental health.

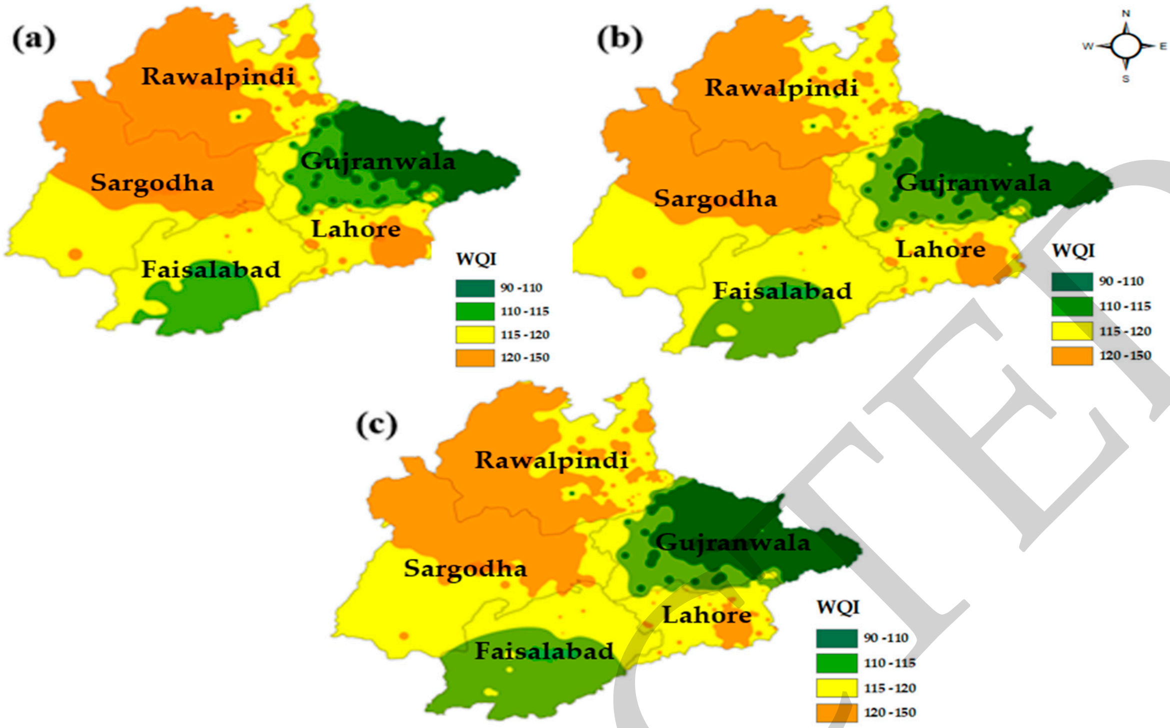

Figure 14. (**a**–**c**) Scenario-I (Primary treatment).

Table 9. Impacts of Primary Wastewater Treatment Scenarios on 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, the impact of secondary treatment of wastewater is evaluated. Two stages with different levels of treatment, as shown in Table 9, are established. Figure 15a shows the results of a 65% reduction in the total dissolved solids (TDS), an 80% reduction in bacterial loadings, and a 45% reduction in hardness by wastewater treatment, and Figure 15b the impact of an 80% reduction in the total dissolved solids (TDS), a 90% reduction in bacterial loadings, and a 55% in hardness. The impact of the reduction in these pollutants after wastewater treatment shows comparable results in the contaminated parts of Lahore, Sargodha, and some areas of Rawalpindi. The impact of these two scenarios on the computed indices is shown in Table 9. The results, demonstrating significant reductions in pollutants, including TDS, bacterial loadings, and hardness, through secondary wastewater treatment spotlight its effectiveness in improving water quality. These outcomes emphasize the critical role of advanced treatment stages in mitigating groundwater pollution, particularly in areas like Lahore and Sargodha, underscoring the necessity of integrating these treatments within environmental management strategies to ensure sustainable water resources and environmental health.

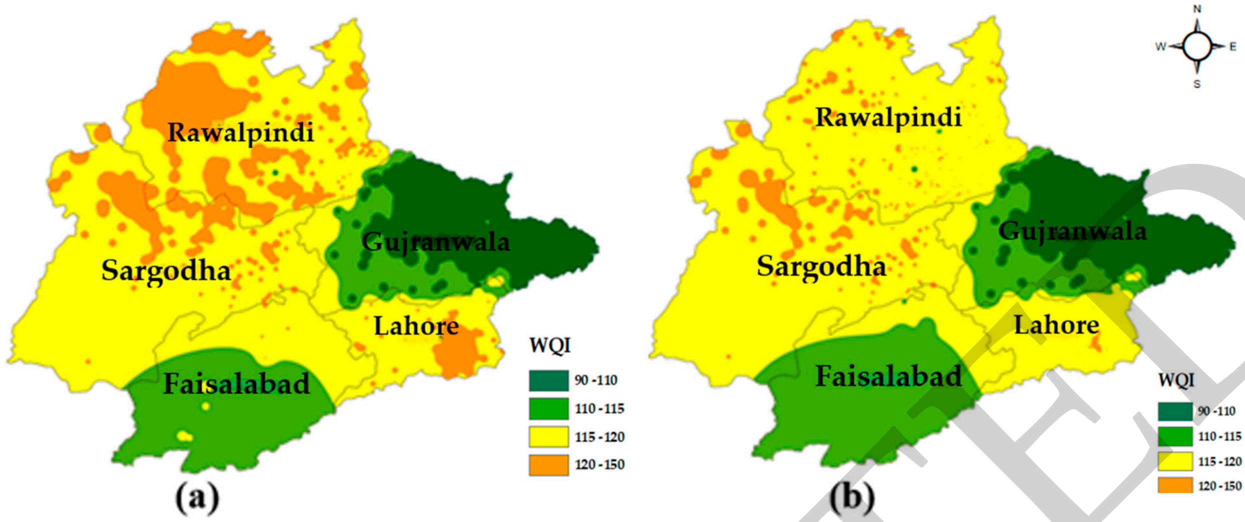

Figure 15. (**a**,**b**) Scenario-II (Secondary treatment).

Scenario-III (Tertiary Treatment)

In this scenario, the tertiary treatment of wastewater is evaluated. Figure 16a shows the impact of a 90% reduction in arsenic and a 75% reduction in the other main pollutant, nitrate, after wastewater treatment, and Figure 16b the impact of a 95% reduction in arsenic and a 45% reduction in nitrate. The results shown in Table 9 show that tertiary treatment improved the quality of water in the study area by 41%. The findings, illustrating substantial reductions in major pollutants through tertiary wastewater treatment, such as a 90% decrease in arsenic and a 75% reduction in nitrate, underscore the significant efficacy of this treatment stage in improving water quality. These results offer critical insights for environmental management strategies. They emphasize the pivotal role of advanced treatment processes in mitigating groundwater pollution, advocating for the implementation and prioritization of such treatments in broader environmental management frameworks to safeguard water resources and public health.

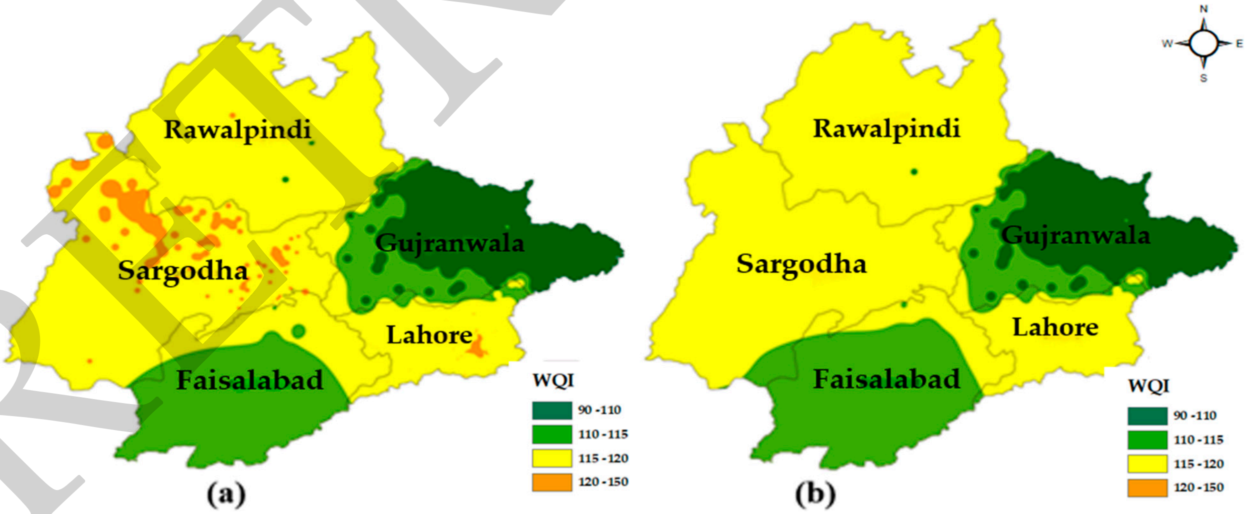

Figure 16. (**a**,**b**) Scenario-III (Tertiary treatment).

4. Conclusions

The findings of this study reveal a critical concern regarding groundwater pollution, prominently attributed to microbial contaminants surpassing acceptable thresholds. An alarming 27% and 19% of samples exhibited excessive levels of total coliforms and *E. coli*, respectively, significantly breaching safety standards. Additionally, concerning levels of arsenic (9%), iron (7%), and nitrate (6%) further accentuate the multifaceted pollution affecting groundwater quality. This analysis, relying on the Water Quality Index (*WQI*), vividly delineates the dire situation, indicating that water in 38% of the study area is unfit for drinking purposes, with a mere 11% meeting the requisite standards. The distressing revelation that in specific divisions—Sargodha, Sheikhupura, Faisalabad, Chiniot, and Rawalpindi—water quality falls significantly below WHO standards highlights the urgent need for remedial actions to ensure safe drinking water.

The identified pollution sources vary across divisions, with each division grappling with distinct challenges. Sargodha contends with elevated TDS, hardness, nitrate, and chloride levels, while Lahore faces arsenic, TDS, and nitrate issues. Notably, microbial contamination emerges as a pervasive challenge across all divisions. Furthermore, the study illuminates the pivotal role of urbanization-induced land use and land cover changes in exacerbating groundwater quality depletion, notably in urbanized regions.

Despite the comprehensive analysis, the study acknowledges certain limitations that warrant consideration. The reliance on available data might have led to certain pollutant sources being overlooked, potentially underestimating their impact on groundwater quality. Moreover, uncertainties persist in modeling and extrapolating findings across the entire area, possibly introducing inaccuracies.

Addressing the identified challenges necessitates a strategic approach and stringent action plans. The proposed mitigation strategies center on eradicating heavy metals and microbial pollution. This demands heightened government interventions, fortifying existing strategies, and ensuring the provision of safe water. Integrating the generated maps into environmental protection initiatives and groundwater safeguarding measures will enhance decision-making processes and policy implementations. Looking ahead, future research endeavors must delve deeper into identifying and assessing additional pollutant sources to ensure sustainable groundwater quality. Collaborative efforts and innovative methodologies will be pivotal in addressing these concerns and safeguarding precious groundwater resources for future generations.

Author Contributions: All authors were involved in the intellectual elements of this paper. M.U.M., S.H. (Saif Haider) and M.R. designed the research, investigation, and methodology, wrote the manuscript, and carried out the validation. S.H. (Saif Haider) and I.N. conducted the research, wrote the manuscript, and carried out the investigation, methodology, and validation. S.H. (Salim Heddam), F.A., I.E., A.A., S.S.S. and C.B.P. carried out the investigation, wrote the original draft and methodology, carried out the review, editing, and formal analysis, and provided the resources that helped in the data arrangement and analysis. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Deputyship for Research & Innovation, Ministry of Education in Saudi Arabia, through project no. IFKSURC-1-7307.

Data Availability Statement: The data are not publicly available due to further research.

Acknowledgments: The authors extend their appreciation to the Deputyship for Research & Innovation, Ministry of Education in Saudi Arabia, for funding this research work through project no. IFKSURC-1-7307.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Foster, S.; Hirata, R.; Gomes, D.; D'Elia, M.; Paris, M. *Groundwater Quality Protection: A Guide for Water Utilities, Municipal Authorities, and Environment Agencies*; World Bank Publications; The World Bank Group: Washington, DC, USA, 2002.
2. Nair, I.S.; Rajaveni, S.P.; Schneider, M.; Elango, L. Geochemical and Isotopic Signatures for the Identification of Seawater Intrusion in an Alluvial Aquifer. *J. Earth Syst. Sci.* **2015**, *124*, 1281–1291. [CrossRef]
3. Alshehri, F.; Abdelrahman, K. Integrated Approach for the Investigation of Groundwater Quality Using Hydrochemical and Geostatistical Analyses in Wadi Fatimah, Western Saudi Arabia. *Front. Earth Sci.* **2023**, *11*, 1166153. [CrossRef]
4. Bartram, J.; Ballance, R. *Water Quality Monitoring: A Practical Guide to the Design and Implementation of Freshwater Quality Studies and Monitoring Programmes*; CRC Press: Boca Raton, FL, USA, 1996; ISBN 0419223207.

5. Haq, M.A.; Jilani, A.K.; Prabu, P. Deep Learning Based Modeling of Groundwater Storage Change. *Comput. Mater. Contin.* **2021**, *70*, 4599–4617.
6. Mangan, P.; Pandi, D.; Haq, M.A.; Sinha, A.; Nagarajan, R.; Dasani, T.; Keshta, I.; Alshehri, M. Analytic Hierarchy Process Based Land Suitability for Organic Farming in the Arid Region. *Sustainability* **2022**, *14*, 4542. [CrossRef]
7. Sayato, Y. WHO Guidelines for Drinking-Water Quality. *Eisei Kagaku* **1989**, *35*, 307–312. [CrossRef]
8. Khan, K.; Lu, Y.; Khan, H.; Zakir, S.; Khan, S.; Khan, A.A.; Wei, L.; Wang, T. Health Risks Associated with Heavy Metals in the Drinking Water of Swat, Northern Pakistan. *J. Environ. Sci.* **2013**, *25*, 2003–2013. [CrossRef] [PubMed]
9. Muhammad, S.; Shah, M.T.; Khan, S. Arsenic Health Risk Assessment in Drinking Water and Source Apportionment Using Multivariate Statistical Techniques in Kohistan Region, Northern Pakistan. *Food Chem. Toxicol.* **2010**, *48*, 2855–2864. [CrossRef]
10. Bodrud-Doza, M.D.; Islam, A.R.M.T.; Ahmed, F.; Das, S.; Saha, N.; Rahman, M.S. Characterization of Groundwater Quality Using Water Evaluation Indices, Multivariate Statistics and Geostatistics in Central Bangladesh. *Water Sci.* **2016**, *30*, 19–40. [CrossRef]
11. Memon, M.; Soomro, M.S.; Akhtar, M.S.; Memon, K.S. Drinking Water Quality Assessment in Southern Sindh (Pakistan). *Environ. Monit. Assess.* **2011**, *177*, 39–50. [CrossRef]
12. Khan, S.; Shahnaz, M.; Jehan, N.; Rehman, S.; Shah, M.T.; Din, I. Drinking Water Quality and Human Health Risk in Charsadda District, Pakistan. *J. Clean. Prod.* **2013**, *60*, 93–101. [CrossRef]
13. Azizullah, A.; Khattak, M.N.K.; Richter, P.; Häder, D.-P. Water Pollution in Pakistan and Its Impact on Public Health—A Review. *Environ. Int.* **2011**, *37*, 479–497. [CrossRef] [PubMed]
14. 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] [PubMed]
15. Ayaz, S.; Khan, S.; Khan, S.N.; Bibi, F.; Shamas, S.; Akhtar, M. Prevalence of Zoonotic Parasites in Drinking Water of Three Districts of Khyber Pakhtunkhwa Province, Pakistan. *Pak. J. Life Soc. Sci.* **2011**, *9*, 67–69.
16. Abdel-Satar, A.M.; Ali, M.H.; Goher, M.E. Indices of Water Quality and Metal Pollution of Nile River, Egypt. *Egypt. J. Aquat. Res.* **2017**, *43*, 21–29. [CrossRef]
17. Bhuiyan, M.A.H.; Rakib, M.A.; Dampare, S.B.; Ganyaglo, S.; Suzuki, S. Surface Water Quality Assessment in the Central Part of Bangladesh Using Multivariate Analysis. *KSCE J. Civ. Eng.* **2011**, *15*, 995–1003. [CrossRef]
18. Chaurasia, A.K.; Pandey, H.K.; Tiwari, S.K.; Prakash, R.; Pandey, P.; Ram, A. Groundwater Quality Assessment Using Water Quality Index (WQI) in Parts of Varanasi District, Uttar Pradesh, India. *J. Geol. Soc. India* **2018**, *92*, 76–82. [CrossRef]
19. Ewaid, S.H.; Abed, S.A. Water Quality Index for Al-Gharraf River, Southern Iraq. *Egypt. J. Aquat. Res.* **2017**, *43*, 117–122. [CrossRef]
20. Krishna Kumar, S.; Logeshkumaran, A.; Magesh, N.S.; Godson, P.S.; Chandrasekar, N. Hydro-Geochemistry and Application of Water Quality Index (WQI) for Groundwater Quality Assessment, Anna Nagar, Part of Chennai City, Tamil Nadu, India. *Appl. Water Sci.* **2015**, *5*, 335–343. [CrossRef]
21. Ponsadailakshmi, S.; Sankari, S.G.; Prasanna, S.M.; Madhurambal, G. Evaluation of Water Quality Suitability for Drinking Using Drinking Water Quality Index in Nagapattinam District, Tamil Nadu in Southern India. *Groundw. Sustain. Dev.* **2018**, *6*, 43–49. [CrossRef]
22. Yousefi, M.; Saleh, H.N.; Mohammadi, A.A.; Mahvi, A.H.; Ghadrpoori, M.; Suleimani, H. Data on Water Quality Index for the Groundwater in Rural Area Neyshabur County, Razavi Province, Iran. *Data Br.* **2017**, *15*, 901–907. [CrossRef]
23. De La Mora-Orozco, C.; Flores-Lopez, H.; Rubio-Arias, H.; Chavez-Duran, A.; Ochoa-Rivero, J. Developing a Water Quality Index (WQI) for an Irrigation Dam. *Int. J. Environ. Res. Public Health* **2017**, *14*, 439. [CrossRef] [PubMed]
24. 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]
25. Effendi, H.; Wardiatno, Y. Water Quality Status of Ciambulawung River, Banten Province, Based on Pollution Index and NSF-WQI. *Procedia Environ. Sci.* **2015**, *24*, 228–237. [CrossRef]
26. Cordoba, E.B.; Martinez, A.C.; Ferrer, E.V. Water Quality Indicators: Comparison of a Probabilistic Index and a General Quality Index. The Case of the Confederación Hidrográfica Del Júcar (Spain). *Ecol. Indic.* **2010**, *10*, 1049–1054. [CrossRef]
27. Khosravi, R.; Eslami, H.; Almodaresi, S.A.; Heidari, M.; Fallahzadeh, R.A.; Taghavi, M.; Khodadadi, M.; Peirovi, R. Use of Geographic Information System and Water Quality Index to Assess Groundwater Quality for Drinking Purpose in Birjand City, Iran. *Desalin Water Treat* **2017**, *67*, 74–83. [CrossRef]
28. Şener, Ş.; Şener, E.; Davraz, A. Evaluation of Water Quality Using Water Quality Index (WQI) Method and GIS in Aksu River (SW-Turkey). *Sci. Total Environ.* **2017**, *584*, 131–144. [CrossRef] [PubMed]
29. Daud, M.K.; Nafees, M.; Ali, S.; Rizwan, M.; Bajwa, R.A.; Shakoor, M.B.; Arshad, M.U.; Chatha, S.A.S.; Deeba, F.; Murad, W. Drinking Water Quality Status and Contamination in Pakistan. *BioMed Res. Int.* **2017**, *2017*, 7908183. [CrossRef]
30. Li, H.; Smith, C.D.; Wang, L.; Li, Z.; Xiong, C.; Zhang, R. Combining Spatial Analysis and a Drinking Water Quality Index to Evaluate Monitoring Data. *Int. J. Environ. Res. Public Health* **2019**, *16*, 357. [CrossRef]
31. Dudley, R.W.; Hirsch, R.M.; Archfield, S.A.; Blum, A.G.; Renard, B. Low Streamflow Trends at Human-Impacted and Reference Basins in the United States. *J. Hydrol.* **2020**, *580*, 124254. [CrossRef]
32. Webster, R.; Oliver, M.A. *Geostatistics for Environmental Scientists*; John Wiley & Sons: Hoboken, NJ, USA, 2007; ISBN 0470517263.
33. Robinson, T.P.; Metternicht, G. Testing the Performance of Spatial Interpolation Techniques for Mapping Soil Properties. *Comput. Electron. Agric.* **2006**, *50*, 97–108. [CrossRef]

34. Wu, J.; Norvell, W.A.; Welch, R.M. Kriging on Highly Skewed Data for DTPA-Extractable Soil Zn with Auxiliary Information for PH and Organic Carbon. *Geoderma* **2006**, *134*, 187–199. [CrossRef]
35. Khan, A.R.; Rafique, M.; Rahman, S.U.; Basharat, M.; Shahzadi, C.; Ahmed, I. Geo-Spatial Analysis of Radon in Spring and Well Water Using Kriging Interpolation Method. *Water Supply* **2019**, *19*, 222–235. [CrossRef]
36. Arslan, H. Spatial and Temporal Mapping of Groundwater Salinity Using Ordinary Kriging and Indicator Kriging: The Case of Bafra Plain, Turkey. *Agric. Water Manag.* **2012**, *113*, 57–63. [CrossRef]
37. Johnson, C.D.; Nandi, A.; Joyner, T.A.; Luffman, I. Iron and Manganese in Groundwater: Using Kriging and GIS to Locate High Concentrations in Buncombe County, North Carolina. *Groundwater* **2018**, *56*, 87–95. [CrossRef] [PubMed]
38. Liang, C.-P.; Chen, J.-S.; Chien, Y.-C.; Chen, C.-F. Spatial Analysis of the Risk to Human Health from Exposure to Arsenic Contaminated Groundwater: A Kriging Approach. *Sci. Total Environ.* **2018**, *627*, 1048–1057. [CrossRef] [PubMed]
39. Mir, A.; Piri, J.; Kisi, O. Spatial Monitoring and Zoning Water Quality of Sistan River in the Wet and Dry Years Using GIS and Geostatistics. *Comput. Electron. Agric.* **2017**, *135*, 38–50. [CrossRef]
40. Murphy, R.R.; Curriero, F.C.; Ball, W.P. Comparison of Spatial Interpolation Methods for Water Quality Evaluation in the Chesapeake Bay. *J. Environ. Eng.* **2010**, *136*, 160–171. [CrossRef]
41. Sheikhy Narany, T.; Firuz Ramli, M.; Zaharin Aris, A.; Azmin Sulaiman, W.N.; Fakharian, K. Spatial Assessment of Groundwater Quality Monitoring Wells Using Indicator Kriging and Risk Mapping, Amol-Babol Plain, Iran. *Water* **2013**, *6*, 68–85. [CrossRef]
42. Tiwari, K.; Goyal, R.; Sarkar, A. GIS-Based Spatial Distribution of Groundwater Quality and Regional Suitability Evaluation for Drinking Water. *Environ. Process.* **2017**, *4*, 645–662. [CrossRef]
43. Horton, R.K. An Index Number System for Rating Water Quality. *J. Water Pollut. Control Fed.* **1965**, *37*, 300–305.
44. Tyagi, S.; Sharma, B.; Singh, P.; Dobhal, R. Water Quality Assessment in Terms of Water Quality Index. *Am. J. Water Resour.* **2013**, *1*, 34–38. [CrossRef]
45. Naz, I.; Ahmad, I.; Aslam, R.W.; Quddoos, A.; Yaseen, A. Integrated Assessment and Geostatistical Evaluation of Groundwater Quality through Water Quality Indices. *Water* **2024**, *16*, 63. [CrossRef]
46. Sahu, P.; Sikdar, P.K. Hydrochemical Framework of the Aquifer in and around East Kolkata Wetlands, West Bengal, India. *Environ. Geol.* **2008**, *55*, 823–835. [CrossRef]
47. Ketata, M.; Gueddari, M.; Bouhlila, R. Use of Geographical Information System and Water Quality Index to Assess Groundwater Quality in El Khairat Deep Aquifer (Enfidha, Central East Tunisia). *Arab. J. Geosci.* **2012**, *5*, 1379–1390. [CrossRef]
48. Rabeiy, R.E. Assessment and Modeling of Groundwater Quality Using WQI and GIS in Upper Egypt Area. *Environ. Sci. Pollut. Res.* **2018**, *25*, 30808–30817. [CrossRef]
49. Kawo, N.S.; Karuppannan, S. Groundwater Quality Assessment Using Water Quality Index and GIS Technique in Modjo River Basin, Central Ethiopia. *J. Afr. Earth Sci.* **2018**, *147*, 300–311. [CrossRef]
50. Wong, Y.J.; Shimizu, Y.; He, K.; Nik Sulaiman, N.M. Comparison among Different ASEAN Water Quality Indices for the Assessment of the Spatial Variation of Surface Water Quality in the Selangor River Basin, Malaysia. *Environ. Monit. Assess.* **2020**, *192*, 644. [CrossRef] [PubMed]
51. Wong, Y.J.; Shimizu, Y.; Kamiya, A.; Maneechot, L.; Bharambe, K.P.; Fong, C.S.; Nik Sulaiman, N.M. Application of Artificial Intelligence Methods for Monsoonal River Classification in Selangor River Basin, Malaysia. *Environ. Monit. Assess.* **2021**, *193*, 438. [CrossRef]
52. Mahmood, K.; Rana, A.D.; Tariq, S.; Kanwal, S.; Ali, R.; Haidar, A. Groundwater Levels Susceptibility to Degradation in Lahore Metropolitan. *Depression* **2011**, *150*, 1–8.
53. Vadde, K.K.; Wang, J.; Cao, L.; Yuan, T.; McCarthy, A.J.; Sekar, R. Assessment of Water Quality and Identification of Pollution Risk Locations in Tiaoxi River (Taihu Watershed), China. *Water* **2018**, *10*, 183. [CrossRef]
54. 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]
55. Hussainzadeh, J.; Samani, S.; Mahaqi, A. Investigation of the Geochemical Evolution of Groundwater Resources in the Zanjan Plain, NW Iran. *Environ. Earth Sci.* **2023**, *82*, 123. [CrossRef]
56. Palanisamy, M.; Krishnan, T.R.; Rahaman, A.S.; Jothiramalingam, K.; Thiyagarajan, I.; Kumar, S.P. Geochemical Characterisation and Geostatistical Evaluation of Groundwater Suitability: A Case Study in Perambalur District, Tamil Nadu, India. *Environ. Sci. Pollut. Res.* **2023**, *30*, 62653–62674. [CrossRef] [PubMed]
57. Kiyani, V.; Esmaili, A.; Alijani, F.; Samani, S.; Vasić, L. Investigation of Drainage Structures in the Karst Aquifer System through Turbidity Anomaly, Hydrological, Geochemical and Stable Isotope Analysis (Kiyan Springs, Western Iran). *Environ. Earth Sci.* **2022**, *81*, 517. [CrossRef]
58. 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]
59. Abbasnia, A.; Yousefi, N.; Mahvi, A.H.; Nabizadeh, R.; Radfard, M.; Yousefi, M.; Alimohammadi, M. Evaluation of Groundwater Quality Using Water Quality Index and Its Suitability for Assessing Water for Drinking and Irrigation Purposes: Case Study of Sistan and Baluchistan Province (Iran). *Hum. Ecol. Risk Assess. Int. J.* **2019**, *25*, 988–1005. [CrossRef]
60. Abbasnia, A.; Radfard, M.; Mahvi, A.H.; Nabizadeh, R.; Yousefi, M.; Soleimani, H.; Alimohammadi, M. Groundwater Quality Assessment for Irrigation Purposes Based on Irrigation Water Quality Index and Its Zoning with GIS in the Villages of Chabahar, Sistan and Baluchistan, Iran. *Data Br.* **2018**, *19*, 623–631. [CrossRef]

61. Ladson, A.R.; White, L.J.; Doolan, J.A.; Finlayson, B.L.; Hart, B.T.; Lake, P.S.; Tilleard, J.W. Development and Testing of an Index of Stream Condition for Waterway Management in Australia. *Freshw. Biol.* **1999**, *41*, 453–468. [CrossRef]
62. Chatterjee, R.; Tarafder, G.; Paul, S. Groundwater Quality Assessment of Dhanbad District, Jharkhand, India. *Bull. Eng. Geol. Environ.* **2010**, *69*, 137–141. [CrossRef]
63. 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]
64. 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]
65. Malik, S.; Malik, S. Maternal Influence on Youth Radicalization–A Case Study of District Multan. *J. Contemp. Stud.* **2021**, *10*, 38–58.
66. 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]
67. Water Sector Task Force. *A Productive and Water-Secure Pakistan: Infrastructure, Institutions, Strategy. The Report of the Water Sector Task Force of the Friends of Democratic Pakistan*; Water Sector Task Force: Islamabad, Pakistan, 2012; Available online: http//www.waterinfo.net.pk (accessed on 24 July 2023).
68. Yasin, H.Q.; Breadsell, J.; Tahir, M.N. Climate-Water Governance: A Systematic Analysis of the Water Sector Resilience and Adaptation to Combat Climate Change in Pakistan. *Water Policy* **2021**, *23*, 1–35. [CrossRef]
69. 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]
70. Frenken, K. Irrigation in Southern and Eastern Asia in Figures: AQUASTAT Survey-2011. *Water Rep.* **2012**, *37*, 487.
71. 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.* **2021**, *19*, 6502705. [CrossRef]
72. Zhou, G.; Zhang, R.; Huang, S. Generalized Buffering Algorithm. *IEEE Access* **2021**, *9*, 27140–27157. [CrossRef]
73. Pesce, S.F.; Wunderlin, D.A. Use of Water Quality Indices to Verify the Impact of Córdoba City (Argentina) on Suquía River. *Water Res.* **2000**, *34*, 2915–2926. [CrossRef]
74. 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]
75. Dunnette, D.A. A Geographically Variable Water Quality Index Used in Oregon. *J. Water Pollut. Control Fed.* **1979**, *51*, 53–61.
76. Thi Minh Hanh, P.; Sthiannopkao, S.; The Ba, D.; Kim, K.-W. Development of Water Quality Indexes to Identify Pollutants in Vietnam's Surface Water. *J. Environ. Eng.* **2011**, *137*, 273–283. [CrossRef]
77. Juwana, I.; Muttil, N.; Perera, B.J.C. Indicator-Based Water Sustainability Assessment—A Review. *Sci. Total Environ.* **2012**, *438*, 357–371. [CrossRef]
78. Malczewski, J. GIS-Based Land-Use Suitability Analysis: A Critical Overview. *Prog. Plann.* **2004**, *62*, 3–65. [CrossRef]
79. Chow, T.E.; Sadler, R. The Consensus of Local Stakeholders and Outside Experts in Suitability Modeling for Future Camp Development. *Landsc. Urban Plan.* **2010**, *94*, 9–19. [CrossRef]
80. Saaty, T.L. A Scaling Method for Priorities in Hierarchical Structures. *J. Math. Psychol.* **1977**, *15*, 234–281. [CrossRef]
81. Ishizaka, A.; Labib, A. Analytic Hierarchy Process and Expert Choice: Benefits and Limitations. *OR Insight* **2009**, *22*, 201–220. [CrossRef]
82. Saaty, R.W. The Analytic Hierarchy Process—What It Is and How It Is Used. *Math. Model.* **1987**, *9*, 161–176. [CrossRef]
83. Pappaka, R.K.; Somagouni, S.G.; Chinthala, K.; Nakkala, A.B. Appraisal of groundwater quality for suitability of drinking and irrigation purposes of pandameru river basin, anantapur district, AP, India. *Arab. J. Geosci.* **2024**, *17*, 23. [CrossRef]
84. 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]
85. Sarkar, K.; Majumder, M. Application of AHP-Based Water Quality Index for Quality Monitoring of Peri-Urban Watershed. *Environ. Dev. Sustain.* **2021**, *23*, 1780–1798. [CrossRef]
86. 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]
87. Haider, S.; Masood, M.U.; Rashid, M.; Alshehri, F. Simulation of the Potential Impacts of Projected Climate and Land Use Change on Runoff under CMIP6 Scenarios. *Water* **2023**, *15*, 3421. [CrossRef]
88. Masood, M.U.; Haider, S.; Rashid, M.; Aldlemy, M.S.; Pande, C.B.; Đurin, B.; Homod, R.Z.; Alshehri, F.; Elkhrachy, I. Quantifying the Impacts of Climate and Land Cover Changes on the Hydrological Regime of a Complex Dam Catchment Area. *Sustainability* **2023**, *15*, 15223. [CrossRef]
89. Shabahat, S.; Raza, A.; Haider, S.; Masood, M.U.; Rashid, M. Investigating the Groundwater Recharge Potential in the Upper Rechna Doab. In Proceedings of the 2nd National Conference on Sustainable Water Resources Management (SWRM-22), Lahore, Pakistan, 16 November 2022; Volume 8670.
90. Hassan, S.; Masood, M.U.; Haider, S.; Anjum, M.N.; Hussain, F.; Ding, Y.; Shangguan, D.; Rashid, M.; Nadeem, M.U. Investigating the Effects of Climate and Land Use Changes on Rawal Dam Reservoir Operations and Hydrological Behavior. *Water* **2023**, *15*, 2246. [CrossRef]

91. Nagra, M.; Masood, M.U.; Haider, S.; Rashid, M. Assessment of Spatiotemporal Droughts Through Machine Learning Algorithm Over Pakistan. In Proceedings of the 2nd National Conference on Sustainable Water Resources Management (SWRM-22), Lahore, Pakistan, 16 November 2022; Volume 8670.
92. Masood, M.U.; Khan, N.M.; Haider, S.; Anjum, M.N.; Chen, X.; Gulakhmadov, A.; Iqbal, M.; Ali, Z.; Liu, T. Appraisal of Land Cover and Climate Change Impacts on Water Resources: A Case Study of Mohmand Dam Catchment, Pakistan. *Water* **2023**, *15*, 1313. [CrossRef]
93. Haider, S.; Masood, M.U.; Rashid, M.; Ali, T.; Pande, C.B.; Alshehri, F.; Elkhrachy, I. Assessment of Rainwater Harvesting Potential for Urban Area under Climate and Land Use Changes Using Geo-Informatics Technology. *Urban Clim.* **2023**, *52*, 101721. [CrossRef]
94. Cotruvo, J.A. 2017 WHO Guidelines for Drinking Water Quality: First Addendum to the Fourth Edition. *J.-Am. Water Work. Assoc.* **2017**, *109*, 44–51. [CrossRef]
95. Balakrishnan, P.; Saleem, A.; Mallikarjun, N.D. Groundwater Quality Mapping Using Geographic Information System (GIS): A Case Study of Gulbarga City, Karnataka, India. *Afr. J. Environ. Sci. Technol.* **2011**, *5*, 1069–1084. [CrossRef]
96. Chandel, R.K.T.S. Quality of Ground Water of Jaipur City, Rajasthan (India) and Its Suitability for Domestic and Irrigation Purpose. *Appl. Ecol. Environ. Res.* **2008**, *6*, 79–88.
97. Gupta, P.; Vishwakarma, M.; Rawtani, P.M. Assessment of Water Quality Parameters of Kerwa Dam for Drinking Suitability. *Int. J. Theor. Appl. Sci.* **2009**, *1*, 53–55.
98. 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] [PubMed]
99. Choudhary, R.; Rawtani, P.; Vishwakarma, M. Comparative Study of Drinking Water Quality Parameters of Three Manmade Reservoirs i.e. Kolar, Kaliasote and Kerwa Dam. *Curr. World Environ.* **2011**, *6*, 145–149. [CrossRef]
100. 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] [PubMed]
101. Hasan, M.; Shang, Y.; Akhter, G.; Jin, W. Evaluation of Groundwater Suitability for Drinking and Irrigation Purposes in Toba Tek Singh District, Pakistan. *Irrig. Drain. Syst. Eng* **2017**, *6*, 185.
102. Sarda, P.; Sadgir, P. Assessment of Multi Parameters of Water Quality in Surface Water Bodies-a Review. *Int. J. Res. Appl. Sci. Eng. Technol.* **2015**, *3*, 331–336.
103. National Research Council. *Fluoride in Drinking Water: A Scientific Review of EPA's Standards*; The National Academies Press: Washington, DC, USA, 2006; 530p, ISBN 978-0-309-10128-8. [CrossRef]
104. Karim, M.D.M. Arsenic in Groundwater and Health Problems in Bangladesh. *Water Res.* **2000**, *34*, 304–310. [CrossRef]
105. Rasheed, H.; Jaleel, F.; Nisar, M.F. Analyzing the Status of Heavy Metals in Irrigation Water in Suburban Areas of Bahawalpur City, Pakistan. *AEJAES* **2014**, *14*, 732–738.
106. Masood, N.; Batool, S.; Farooqi, A. Groundwater Pollution in Pakistan. In *Global Groundwater*; Elsevier: Amsterdam, The Netherlands, 2021; pp. 309–322.
107. Soomro, Z.A.; Khokhar, D.M.I.A.; Hussain, W.; Hussain, M. *Drinking Water Quality Challenges in Pakistan*; Pakistan Council of Research in Water Resources: Lahore, Pakistan, 2011; pp. 17–28.
108. Bibi, S.; Khan, R.L.; Nazir, R.; Khan, P.; Rehman, H.U.; Shakir, S.K.; Naz, S.; Waheed, M.A.; Jan, R. Heavy Metals Analysis in Drinking Water of Lakki Marwat District, KPK, Pakistan. *World Appl. Sci. J.* **2016**, *34*, 15–19.
109. Shafeeque, M.; Sarwar, A.; Basit, A.; Mohamed, A.Z.; Rasheed, M.W.; Khan, M.U.; Buttar, N.A.; Saddique, N.; Asim, M.I.; Sabir, R.M. Quantifying the Impact of the Billion Tree Afforestation Project (BTAP) on the Water Yield and Sediment Load in the Tarbela Reservoir of Pakistan Using the SWAT Model. *Land* **2022**, *11*, 1650. [CrossRef]
110. Gao, C.; Hao, M.; Chen, J.; Gu, C. Simulation and design of joint distribution of rainfall and tide level in Wuchengxiyu Region, China. *Urban Clim.* **2021**, *40*, 101005. [CrossRef]
111. Xu, Z.; Li, X.; Li, J.; Xue, Y.; Jiang, S.; Liu, L.; Luo, Q.; Wu, K.; Zhang, N.; Feng, Y.; et al. Characteristics of Source Rocks and Genetic Origins of Natural Gas in Deep Formations, Gudian Depression, Songliao Basin, NE China. *ACS Earth Space Chem.* **2022**, *6*, 1750–1771. [CrossRef]
112. 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]
113. Anwar, M.S.; Chaudhry, N.A.; Tayyib, M. Qualitative Assessment of Bacteriological Quality and Chlorination Status of Drinking Water in Lahore. *J. Coll. Physicians Surg. JCPSP* **2004**, *14*, 157–160. [PubMed]
114. Rasheed, H.; Altaf, F.; Anwaar, K.; Ashraf, M. *Drinking Water Quality in Pakistan: Current Status and Challenges*; Pakistan Council of Research in Water Resources (PCRWR): Islamabad, Pakistan, 2021; p. 141.
115. Ayesha, A. Pollution of Water Bodies: Challenges and Strategies. *Environ. PIAIP-NESPAK Lahore* **2012**, *11*, 1087–1098.
116. Odonkor, S.T.; Ampofo, J.K. Escherichia Coli as an Indicator of Bacteriological Quality of Water: An Overview. *Microbiol. Res.* **2013**, *4*, e2. [CrossRef]
117. Ahmed, A.; Mustafa, U.; Samad, G. *Economic Appraisal of Rooftop Rainwater Harvesting Technology in Bagh and Battagram Districts Pakistan*; Pakistan Institute of Development Economics: Islamabad, Pakistan, 2012.

118. Islam-Ul-Haq, C.W.A.; Ahmed, C.N. Multifaceted Ground Water Quality and Recharge Mechanism Issues in a Mega-City (Rawalpindi, Pakistan), and Mitigation Strategies. In Proceedings of the 6th International IAHS Ground Water Quality Conference, Fremantle, Australia, 2–7 December 2007.
119. Zaman, M.; Shahid, S.A.; Heng, L.; Zaman, M.; Shahid, S.A.; Heng, L. Irrigation Water Quality. In *Guideline for Salinity Assessment, Mitigation and Adaptation Using Nuclear and Related Techniques*; Springer: Berlin/Heidelberg, Germany, 2018; pp. 113–131.
120. Balachandar, D.; Sundararaj, P.; Murthy, R.K.; Kumaraswamy, K. An Investigation of Groundwater Quality and Its Suitability to Irrigated Agriculture in Coimbatore District, Tamil Nadu, India-A GIS Approach. *Int. J. Environ. Sci.* **2010**, *1*, 176.
121. Noor, R.; Maqsood, A.; Baig, A.; Pande, C.B.; Zahra, S.M.; Saad, A.; Anwar, M.; Singh, S.K. A comprehensive review on water pollution, South Asia Region: Pakistan. *Urban Clim.* **2023**, *48*, 101413. [CrossRef]
122. Khan, F.; Ali, S.; Mayer, C.; Ullah, H.; Muhammad, S. Climate Change and Spatio-Temporal Trend Analysis of Climate Extremes in the Homogeneous Climatic Zones of Pakistan during 1962–2019. *PLoS ONE* **2022**, *17*, e0271626. [CrossRef]
123. Ashraf, M.; Nasir, M.; Khan, M.B.; Umar, F.; Garh, M. Characterization of Ground Water Quality for Irrigation in Tehsil and District Layyah, Punjab Pakistan. *Nat. Sci.* **2013**, *11*, 128–132.
124. Sadashivaiah, C.; Ramakrishnaiah, C.R.; Ranganna, G. Hydrochemical Analysis and Evaluation of Groundwater Quality in Tumkur Taluk, Karnataka State, India. *Int. J. Environ. Res. Public Health* **2008**, *5*, 158–164. [CrossRef] [PubMed]
125. 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]
126. Rashid, M.; Haider, S.; Masood, M.U.; Pande, C.B.; Tolche, A.D.; Alshehri, F.; Costache, R.; Elkhrachy, I. Sustainable Water Management for Small Farmers with Center-Pivot Irrigation: A Hydraulic and Structural Design Perspective. *Sustainability* **2023**, *15*, 16390. [CrossRef]
127. Mazhar, F. Population Growth & Distribution Pattern in Punjab, Pakistan (1998–2017): A Geospatial Approach. *Int. J. Innov. Sci. Res. Technol.* **2018**, *3*, 508–511.
128. Khan, M. Impact of Urbanization on Water Resources of Pakistan: A Review. *NUST J. Eng. Sci.* **2019**, *12*, 1–8. [CrossRef]
129. Basharat, M. Groundwater Environment in Lahore, Pakistan. In *Groundwater Environment in Asian Cities*; Elsevier: Amsterdam, The Netherlands, 2016; pp. 147–184.
130. Varade, A.M.; Yenkie, R.O.; Shende, R.R.; Golekar, R.B.; Wagh, V.M.; Khandare, H.W. Assessment of Water Quality for the Groundwater Resources of Urbanized Part of the Nagpur District, Maharashtra (India). *Am. J. Water Resour.* **2018**, *6*, 89–111.
131. Butt, I.; Iqbal, A. Solid Waste Management and Associated Environmental Issues in Lahore. *Pak. Geogr. Rev.* **2007**, *62*, 45–50.
132. Akhtar, N.; Ishak, M.I.S.; Ahmad, M.I.; Umar, K.; Md Yusuff, M.S.; Anees, M.T.; Qadir, A.; Ali Almanasir, Y.K. 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]
133. Al-Rekabi, W.S.; Qiang, H.; Qiang, W.W. Improvements in Wastewater Treatment Technology. *Pak. J. Nutr.* **2007**, *6*, 104–110.
134. Zhang, Z.; Han, Y.; Xiao, F.-S.; Qiu, S.; Zhu, L.; Wang, R.; Yu, Y.; Zhang, Z.; Zou, B.; Wang, Y. Mesoporous Aluminosilicates with Ordered Hexagonal Structure, Strong Acidity, and Extraordinary Hydrothermal Stability at High Temperatures. *J. Am. Chem. Soc.* **2001**, *123*, 5014–5021. [CrossRef]
135. Monteiro, S.; Rente, D.; Cunha, M.V.; Marques, T.A.; Cardoso, E.; Vilaça, J.; Coelho, N.; Brôco, N.; Carvalho, M.; Santos, R. Discrimination and Surveillance of Infectious Severe Acute Respiratory Syndrome Coronavirus 2 in Wastewater Using Cell Culture and RT-QPCR. *Sci. Total Environ.* **2022**, *815*, 152914. [CrossRef] [PubMed]
136. Alshehri, F.; Sultan, M.; Karki, S.; Alwagdani, E.; Alsefry, S.; Alharbi, H.; Sahour, H.; Sturchio, N. Mapping the distribution of shallow groundwater occurrences using Remote Sensing-based statistical modeling over southwest Saudi Arabia. *Remote Sens.* **2020**, *12*, 1361. [CrossRef]
137. Valero, F.; Barceló, A.; Arbós, R. Electrodialysis Technology: Theory and Applications. *Desalination Trends Technol.* **2011**, *28*, 3–20.
138. Seenivasagan, R.; Ayyasamy, P.M.; Kasimani, R.; Karthika, A.; Rajakumar, S.; Babalola, O.O. Nitrate Removal from Ground Water Through Lab Scale Bioreactor Using Dissimilatory Nitrate Reducer Bacillus Weihenstephanensis (DS45). In *Bioremediation and Sustainable Technologies for Cleaner Environment*; Springer: Berlin/Heidelberg, Germany, 2017; pp. 79–94.
139. Xu, J.; Lan, W.; Ren, C.; Zhou, X.; Wang, S.; Yuan, J. Modeling of coupled transfer of water, heat and solute in saline loess considering sodium sulfate crystallization. *Cold Reg. Sci. Technol.* **2021**, *189*, 103335. [CrossRef]
140. Yin, L.; Wang, L.; Ge, L.; Tian, J.; Yin, Z.; Liu, M.; Zheng, W. Study on the Thermospheric Density Distribution Pattern during Geomagnetic Activity. *Appl. Sci.* **2023**, *13*, 5564. [CrossRef]
141. Zhu, X.; Xu, Z.; Liu, Z.; Liu, M.; Yin, Z.; Yin, L.; Zheng, W. Impact of dam construction on precipitation: A regional perspective. *Mar. Freshw. Res.* **2022**, *74*, 877–890. [CrossRef]
142. 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]
143. Yin, L.; Wang, L.; Keim, B.D.; Konsoer, K.; Yin, Z.; Liu, M.; Zheng, W. Spatial and wavelet analysis of precipitation and river discharge during operation of the Three Gorges Dam, China. *Ecol. Indic.* **2023**, *154*, 110837. [CrossRef]
144. Alshehri, F.; Almadani, S.; El-Sorogy, A.S.; Alwaqdani, E.; Alfaifi, H.J.; Alharbi, T. Influence of seawater intrusion and heavy metals contamination on groundwater quality, Red Sea coast, Saudi Arabia. *Marine Pollut. Bull.* **2021**, *165*, 112094. [CrossRef]

145. 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]
146. Liu, Z.; Xu, J.; Liu, M.; Yin, Z.; Liu, X.; Yin, L.; Zheng, W. Remote sensing and geostatistics in urban water-resource monitoring: A review. *Mar. Freshw. Res.* **2023**, *74*, 747–765. [CrossRef]
147. Zhang, S.; Bai, X.; Zhao, C.; Tan, Q.; Luo, G.; Wang, J.; Li, Q.; Wu, L.; Chen, F.; Li, C.; et al. Global CO_2 Consumption by Silicate Rock Chemical Weathering: Its Past and Future. *Earth's Future* **2021**, *9*, e1938E–e2020E. [CrossRef]
148. Luo, J.; Niu, F.; Lin, Z.; Liu, M.; Yin, G.; Gao, Z. Abrupt increase in thermokarst lakes on the central Tibetan Plateau over the last 50 years. *Catena* **2022**, *217*, 106497. [CrossRef]
149. Li, W.; Wang, C.; Liu, H.; Wang, W.; Sun, R.; Li, M.; Shi, Y.; Zhu, D.; Du, W.; Ma, L.; et al. Fine root biomass and morphology in a temperate forest are influenced more by canopy water addition than by canopy nitrogen addition. *Front. Ecol. Evol.* **2023**, *11*, 1132248. [CrossRef]
150. 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]
151. Li, Q.; Lu, L.; Zhao, Q.; Hu, S. Impact of Inorganic Solutes' Release in Groundwater during Oil Shale In Situ Exploitation. *Water* **2023**, *15*, 172. [CrossRef]
152. 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]
153. Sun, S.; Liu, H.; Zhang, J.; Wang, W.; Xu, P.; Zhud, X.; Wang, Y.; Wan, S. Application of a novel coagulant in reservoir water treatment in Qingdao. *Desalination Water Treat.* **2023**, *284*, 49–60. [CrossRef]