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A GIS-Based Comparative Analysis of Ground Water Quality in Administrative Towns of Lahore City (2014–2024)

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Amidst insufficiency of water reserves, groundwater plays a crucial role in meeting freshwater requirements for households, parks, and horticulture in Lahore city. However, concerns regarding groundwater quality and its associated risk to human health and the environment have intensified due to factors such as rapid urbanization, industrial growth, and over-extraction. Despite different monitoring efforts, the regional variability and uncertainty in groundwater quality necessitate more sophisticated assessment approaches to support optimal decision-making. The purpose of this study is to perform a comparative analysis between traditional Groundwater Quality Index (GQI) evaluation methods and entropy-weighted models. Additionally, it aims to analyze groundwater quality in tubewells across administrative towns in Lahore by utilizing Geographic Information System (GIS) and advanced geospatial techniques. The study incorporates groundwater quality data such as pH, Total Dissolved Solids (TDS), Electrical Conductivity (EC), and heavy metal concentrations into a GIS-based spatial analytic framework. By taking uncertainty in water quality classification into account, both traditional and entropy information theory offer a more adaptable and practical evaluation of groundwater suitability than the other GQI frameworks. The findings of this study show that groundwater quality varies significantly around Lahore, with certain regions showing contamination levels above acceptable bounds. High-risk areas are identified by the study, where water quality metrics point to possible health issues and highlight the necessity of focused measures.

Keywords: Comparative Analysis; Entropy Weighted Model; Groundwater Quality, GIS.

Introduction:

Water is an essential component of all forms of life and has been endorsed as a basic human right. Given its vital importance to all forms of life, it might surprise you to know that only 3% of the Earth's freshwater [1] can be drinkable for human consumption. In many developing countries, access to safe drinking water is still limited. Pakistan is a developing country, so it faces a lot of the same access problems as other developing countries, especially for individuals living in towns and the countryside. Groundwater is the primary source of drinking water in Pakistan; however, this source of freshwater is increasingly being threatened by rapid urbanization, industrial pollution, and climate change [1]. Every year, Pakistan loses between 0.45 to 1.5 meters of groundwater, depending on the location. It causes a lot of stress on aquifers and makes it extremely difficult to allow them to recharge naturally. In several areas, groundwater depths can now be recorded as deep as 46 meters in 2014 [2][3]. The quality and quantity of groundwater are becoming more severe, resulting in serious implications for public health. Waterborne infections are more inclined to occur when untreated wastewater with heavy metals and other contaminants gets into the groundwater. Over three million people in Pakistan are tired from waterborne diseases, and approximately 100,000 of them die from these illnesses [4].

Groundwater contamination has become a persistent concern in Lahore, the second-largest city of Pakistan, and the capital of Punjab. Over the last few decades, multiple studies have shown the city's declining water quality. According to [5], nitrates, sulphates, metals, dissolved gases, soluble organic compounds, and salts frequently contaminate water systems; nonetheless, one in five Pakistanis suffers from waterborne illnesses caused by pollution from multiple sources [6]. An official survey completed across 12 districts in Punjab revealed that around 79% of drinking water samples were contaminated, while 88% of 12 drinking water sources in rural areas were contaminated due to sanitary waste discharge, toxic metals, biological contaminants, and industrial wastewater [1].

Groundwater, primarily supplied by the Water and Sanitation Agency (WASA), constitutes the main source of drinking water in Lahore's administrative towns. This is achieved through a vast infrastructure of tubewells and distribution pipelines. Lahore, one of the most populous and rapidly urbanizing cities in Pakistan, is currently facing significant groundwater quality issues due to rapid urban growth, excessive aquifer extraction, and anthropogenic waste. This study is important as it deals with a major environmental and public health issue, the deterioration of groundwater quality in prominent administrative towns of Lahore city. The provision of clean drinking water necessitates ongoing Geographic Information System (GIS) based methodologies that enable the integration of spatial and attribute data for comprehensive water quality analysis, resulting in more informed decision-making and efficient resource management.

The purpose of this study is to utilize Geographic Information System (GIS) techniques to monitor the groundwater quality of tubewells in the administrative towns of Gulberg and Nishtar. The physicochemical characteristics of the water are evaluated through an application of the Water Quality Index (WQI). Groundwater quality trends for the years 2014 and 2024 are assessed through two approaches: a traditional-based method and Entropy Weighted Models. The purpose of this geostatistical analysis is to give the Ministry of Health, the Environmental Protection Agency (EPA), and the Water and Sanitation Agency (WASA) important information about the quality of the groundwater in Lahore. It might also aid in lowering the high expenses related to waterborne illnesses in the research region. The findings from this research may support interventions to reduce the spread of waterborne diseases, improve the water supply system, and promote sustainable groundwater use in urban areas.

Objectives:

To assess and monitor the spatial distribution of groundwater quality among the administrative towns of Lahore using GIS GIS-based methodology. To compare changes in groundwater quality throughout ten years (2014-2024) with the help of water quality index (WQI)models. Whereas several previous research studies have considered a single approach or time dimension, this allows decision makers to consider the longitudinal, spatially oriented, and comparison-based model.

Study Area:

Lahore, an economic hub and capital of Punjab Province, has latitudes 31.5204° N and longitudes 74.3587° E. It is located on the east bank of the River Ravi and its extent is from the Hudiara Drain in the south and eastward to the border with India. Its population is 10 million, and the total industrial units is 2000. Lahore has a semi-arid climate with an average annual rainfall of over 715mm [7]. The region's modern soils are made up of sand, silt, clay, and loamy clay; however, as one moves further from the River Ravi, the loamy clay content has progressively risen. Considered to be made of unconsolidated alluvial deposits, the aquifers vary in silt, sand, and clay quantity [8].

The Water and Sanitation Agency (WASA) is responsible for providing safe drinking water in Lahore. WASA is supplying 333 litres per capita per day [9]. The WASA has divided its jurisdictions into eight administrative towns, namely Iqbal Town, Gulberg Town, Nishtar Town, Aziz Bhatti Town, Gunj Bakhsh Town, Ravi Town, Shalimar Town, and Jubilee Town [2]. This study focuses on two towns: Gulberg and Nishtar Town, as shown in Figure 1. The drinking water has been contaminated due to increased residential, commercial, and industrial activities. Sewage water enters fresh water due to poor, fractured, and old pipes. Examine the water quality at WASA tubewells in Gulberg and Nishtar Town to identify the contamination in different years and their potential sources. Spatial distribution of contamination level will also be mapped using GIS techniques.

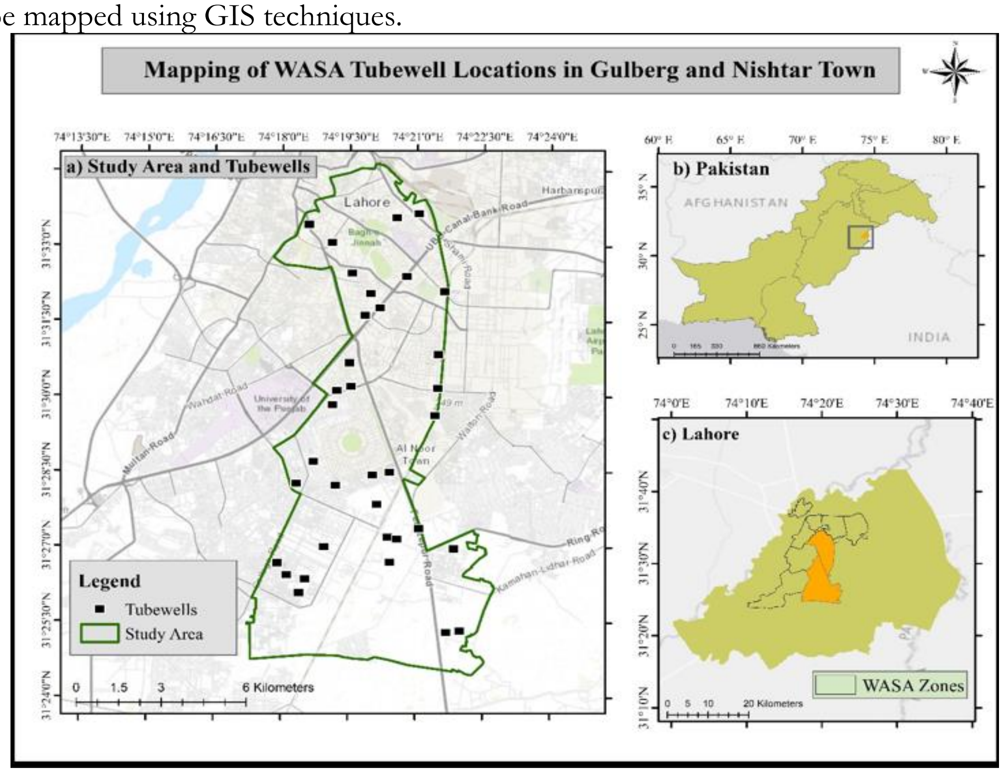

Figure 1. Spatial Distribution of WASA Tubewells in Gulberg and Nishtar Towns. Inset b) and c) place the study area within Pakistan and Lahore, respectively, showing its administrative context and position within WASA zones. a) highlights tubewell locations as black squares within the green outlined study area.

Data Acquisition:

Groundwater quality data for this study were obtained from the WASA laboratory, Lahore. The datasets include information from 35 tubewells across Gulberg and Nishtar towns and cover two different years: 2014 and 2024. It encompasses annual average values of groundwater quality parameters gathered from all of these tubewells. WASA provided data for a total of ten key parameters: potential of hydrogen (pH), turbidity, total dissolved solids (TDS), conductivity, hardness, calcium, magnesium, chloride, bicarbonate, and alkalinity. These averages are calculated per tubewell for each year, enabling comparative analysis of water quality changes over time. The ten-year intervals between the data allow for comparing the groundwater quality trends over the past decade.

Data Manipulation and Processing:

Interpolation Methods:

Water quality parameters were estimated using three interpolation methods: Inverse Distance Weighting (IDW), Ordinary Kriging, and Indicator Co-kriging. Due to its simplicity and effectiveness, IDW is especially helpful in sparse environmental datasets and estimates values by giving nearby points more influence (Setianto & Triandini, n.d.;[10]. However, only turbidity yielded acceptable RMSE values under normalized error scales. Ordinary Kriging is a geostatistical method that uses both distance and spatial autocorrelation to make accurate predictions about pH, with an RMSE of less than 1. This makes it the best method for pH mapping because it gives unbiased estimates and has a low estimation error [4]. Indicator Cokriging was applied to model spatial relationships between correlated parameter pairs (e.g., EC-TDS (mg/L), EC-Cl^-(mg/L), Ca^{2+}Hardness(mg/L), Mg^{2+}Hardness (mg/L), HCO_3^--Alkalinity(mg/L) by converting data into binary indicators based on WHO and EPA-defined thresholds [11][12]. This method had a high level of accuracy (RMSE < 1) and made it possible to make exceedance probability maps. These maps helped with risk assessment and decision-making in places where there wasn't much sampling data.

Table 1. Accuracy of interpolation methods for groundwater quality parameters (2014, 2024) using root mean square error (RMSE) (mg/L), mean standard error (SMD), and average standard error (SEM).

GWQ Parameters	Interpolation Methods	Year 2014			Year 2024		
		RMSE	SMD	SEM	RMSE	SMD	SEM
TDS & Conductivity	Indicator Cokriging	0.39	0.084	0.349	0.347	0	0.369
Chloride & Conductivity		0.5	0.05	0.376	0.364	-0.01	0.378
Calcium & Hardness		0.18	-0.073	0.126	0.222	0.083	0.13
Magnesium & Hardness		0.174	-0.045	0.107	0.181	-0.016	0.178
Bicarbonate & Alkalinity		0.16	0.006	0.496	0.241	-0.028	0.332
Turbidity (NTU)	IDW	0.757	0	0.00	0.439	0	0
pH	Kriging	0.181	-0.02	0.16	0.181	-0.018	0.198

Traditional groundwater quality index (GQI):

The Concentration Index (CI) is the initial and crucial stage in the traditional GIS-based groundwater quality assessment model. The CI can be used to normalize different water quality indicators that may have different units of measurement. CI is the concentration index, X is the interpolated raster derived from IDW, kriging, and indicator cokriging, and T is the threshold values based on WHO and Pakistan's National Environmental Quality Standards (NEQS) [13]. The CI is calculated using the following formula:

$$CI = \frac{X - T}{X + T}$$

Therefore, the rank (R) maps of all the parameters were generated using the following equation:

$$R = 0.5 * CI^2 + 4.5 * CI + 5$$

The weights (W) for each parameter were determined as the mean of the respective rank values. Based on input from field experts and national water quality assessments, the following parameters were classified as high priority: Total Dissolved Solids (TDS), Electrical Conductivity (EC), chloride (Cl^-), and turbidity. By incorporating 45 mean rank values as weights, all parameters are fully reflected in the groundwater quality assessment, both from a spatial perspective and due to their local value. The eventual step of a groundwater quality assessment is to calculate the Groundwater Quality Index (GWQI). The GWQI is an integrated measure, combining several water quality parameters for an intuitive and interpretable score. The index gives a spatially continuous measure of groundwater quality for drinking purposes, and focuses the attention of decision makers on the priority areas for management strategies. The formula for calculating the GWQI is given as:

$$GQI = 100 - \frac{R_1 * W_1 + R_2 * W_2 + \cdots + R_n * W_n}{n}$$

Where GWQI is the groundwater quality index, Rn is the rank raster value of the nth water quality parameter, Wn is the weights assigned to the nth parameter, and n is the total number of parameters considered. This formula originates a weighted average for all the ranked parameters, in accordance with each water quality indicator having a unique weight in the final index.

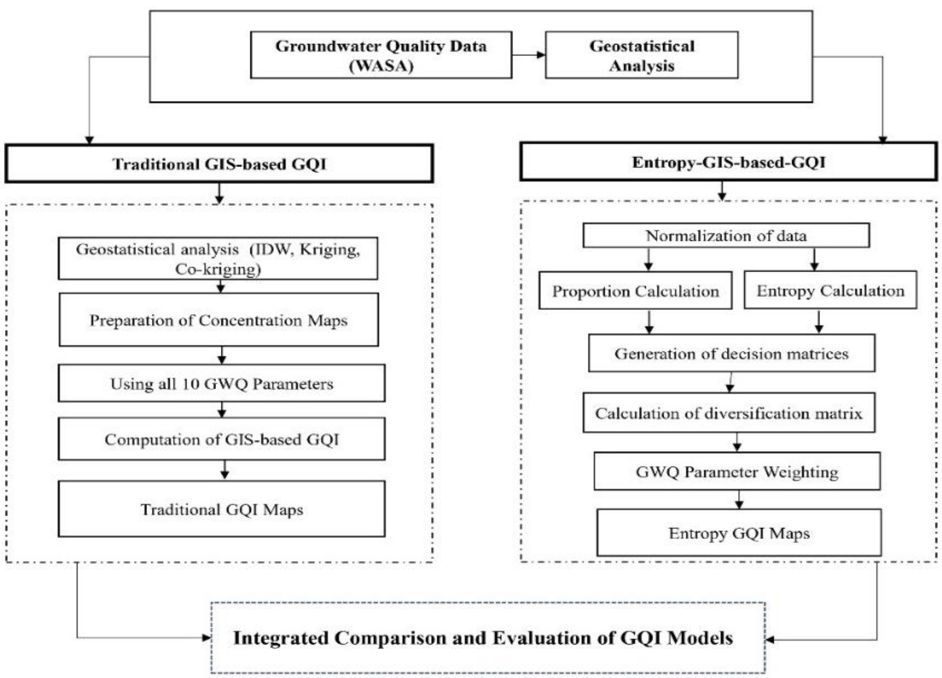

Figure 2. Flowchart depicting the methodology for developing traditional and Entropy GIS-based GQI models.

Shannon's Entropy Weighted Model:

The Shannon Entropy technique is an objective method from information theory, introduced by Claude Shannon in 1948, for determining the importance of groundwater quality parameters. In Multi-criterion Decision Making (MCDM), it assigns the criteria are assigned weights based solely on their data variability. The weights to be granted are chosen according to data variability; human elements or personal perceptions or beliefs have absolutely no bearing on it. The model gathers or quantifies the information value each parameter provides through evaluating the degree of uncertainty or diversity in the dataset employing the variability [14]. The first step in the Shannon Entropy method is to develop the decision matrix, which properly expresses the original dataset formatted for further work. The decision matrix presents the raw values of an array of alternatives across several different criteria. The decision matrix is the starting point for the normalization process and the calculation of entropy. The decision matrix is represented as:

$$X = \begin{cases} x_{11} & x_{21} & x_{1n} \\ x_{m1} & x_{m2} & x_{mn} \end{cases}$$

After generating the raw data matrix, the normalization of the data is performed. Each parameter (criterion) can have different measurements or scales, and in order to compare all values fairly in a direct comparison. Calculate the normalized value by using the following equation:

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}}$$

Where pij is the normalized value of the j-th parameter at the i-th location. $\sum xij\ m$ i=1 is the sum of all values in column j (for the j-th criterion). m is the total number of alternatives (sampling points). After the normalized matrix is constructed, the next step is to calculate the Shannon entropy for each criterion (parameter). Entropy, in this case, assesses the level of disorder or uncertainty in each parameter's data distribution across all sampling sites. To calculate the entropy value of the jth parameter by using the following equation:

$$e_j = -\frac{1}{\ln(m)} \sum_{i=1}^{m} r_{ij} \ln(r_{ij})$$

Where e_{ij} is the entropy of the jth parameter, m is the number of alternatives, r_{ij} is the normalized value of the jth parameter, ln is the natural logarithm of the normalized value, and $\frac{1}{\ln(m)}$ Is the constant defined? Once the entropy values are calculated for the parameters, the next step is to determine the degree of diversification and then the relative weights for each criterion. This process quantifies the actual impact each groundwater quality parameter has in regards to variability or useful information within the overall dataset. The measure of diversification is determined by the equation:

$$d_j = 1 - e_j$$

Where dj is the equivalent information or discriminating power of the parameter, and is the entropy of the jth parameter. The larger the value of dj, the more informative the parameter with greater variability between sampling locations, and therefore greater significance in terms of assessing the quality of groundwater. Once the DJ values are determined, the normalized weights or relative significance of each parameter are found as:

$$W_j = \frac{d_j}{\sum_{j=1}^{n} d_j}$$

Where Wj is the final relative weight of parameter j, $\sum dj\ n\ j$=1 is the sum of all diversification values across parameters. The sum of all is equal to 1 (unity). This procedure ensures that each of the weights is scaled between 0 and 1, and that they reflect the relative importance of the parameter based on its content information.

After calculating the relative weights wj for each parameter using Shannon Entropy, the last step in this process is to calculate the Groundwater Quality Index (GQI), or in some references, the Water Quality Index (WQI). This is achieved by combining the weights with the quality rating scale from the previous step for each parameter. The desired result is one value indicating the level of groundwater quality as a composite on a per-site basis. Calculation of Groundwater Quality Index (GQI) is performed by using the following equation:

$$WQI = \sum_{j=1}^{n} (W_j * q_j)$$

Table 2. Calculation of relative weights using the degree of diversification for each groundwater quality parameter.

GWQ Parameters	Year 2014			Year 2024		
	Entropy	Diversification	Weights	Entropy	Diversification	Weights
TDS & Conductivity	-8611.3	8612.32	0.16	-8197.2	8198.21	0.13
Chloride & Conductivity	-8364.7	8365.66	0.15	-8212.5	8213.48	0.13
Calcium & Hardness	-875.68	876.68	0.02	-10023	10024.1	0.16
Magnesium & Hardness	-10494	10495.47	0.19	-9527.4	9528.43	0.15
Bicarbonate & Alkalinity	-10304	10305.42	0.19	-9605.3	9606.3	0.15
Turbidity	-9832.7	9833.65	0.18	-9666.1	9667.06	0.16
pH	-6950.1	6951.1	0.13	-6910.1	6911.11	0.11

Table 3. Comparative analysis of Traditional GQI and Entropy-Based GQI methods for assessing groundwater quality in 2014 and 2024.

Aspect	Traditional GQI	Entropy-based GQI
Purpose	Analyze spatial and temporal trends in groundwater quality using weighted quality parameters.	Assess groundwater quality variability and uncertainty using probabilistic entropy measures.
2014 Results	Most areas had good to moderate quality; a few excellent zones in the north/southwest; some localized areas of high/severe pollution.	Mixed profile; moderate to severe contamination in central/southern areas; the northern areas showed signs of early deterioration.
2024 Results	Marked improvements; more areas shifted to excellent and good quality, with only a few areas that needed improvement.	Marked improvement; many areas changing from moderate/severe to good/excellent; decreased severe areas, particularly to the north.
Strengths	Straightforward and easy to interpret; identifies hotspots; could assist long-term planning.	Addresses spatial and temporal variability; quantifies uncertainty; applicable for early warning and site-specific management.
Effectiveness	Good for analyzing overall trends and visually identifying water quality classification.	Applicable for detailed assessments, vulnerability indexing, and local intervention planning.

Where wj is the weight of the jth parameter, qj is the quality rating of the jth parameter, and n is the total number of groundwater quality parameters. Higher qj is indicative of poorer water quality (e.g., a value > 100 means that the parameter is above a permissible limit).

Results and Discussions:

Variability of groundwater-quality parameter concentration in the study area:

Spatial interpolation of groundwater quality (GWQ) (2014- 2024) parameters was conducted utilizing Indicator Cokriging, IDW, and Kriging, measured through RMSE, SMD, and SEM. Indicator Cokriging had success with moderately correlated parameters and state conditions such as Calcium & Hardness and Magnesium & Hardness, with low RMSE and SEM. TDS & Conductivity and Chloride & Conductivity had higher RMSE results, meaning greater variability with the parameters. IDW on turbidity yields a lower RMSE value and measurably lower variability, with results indicating that this interpretation was effective for highly variable info. Kriging on pH had low RMSE and SMD values, indicating this method was appropriate for continuous parameters. Interpolation accuracy for use of groundwater quality generally improved over time, and the quality of data obtained and available spatial data coverage for interpolation.

Comparison Between Groundwater Quality Indices:

For assessing the spatial-temporal variation of groundwater quality conditions in the assessment region, the Conventional Groundwater Quality Index (GQI) and Entropy-based GQI methodology using Shannon's Entropy were utilized for the years 2014 and 2024, respectively.

Comparison with Similar Studies:

The groundwater quality of Lahore is slowly improving, consistent with the patterns observed in urban river basins in similar studies. The decrease in the extent of high-risk zones and parameter concentrations demonstrates the effectiveness of policy-level responses. The observed patterns and trends are also consistent with regional studies, thereby improving the degree of confidence in the assessment and broadening its applicability [15]. Lahore is showing groundwater quality improvement in selective urban areas influenced by better wastewater regulation and aquifer recharge efforts. The cited research also noted declining trends in EC, chloride, and TDS consistent with improvements noted at Gulberg and Nishtar Towns. This parallel begets confidence in our GIS-based assessment and illustrates that the regional actions and interventions are demonstrating tangible water quality benefits [16]. Furthermore, the physicochemical quality of drinking water in southern Lahore meets WHO standards, although the majority of the distribution system is bacteriologically contaminated, particularly after the monsoon. Adequate chlorination, upgrades to the infrastructure, and improved drainage will be significant in ensuring the provision of safe drinking water [17].

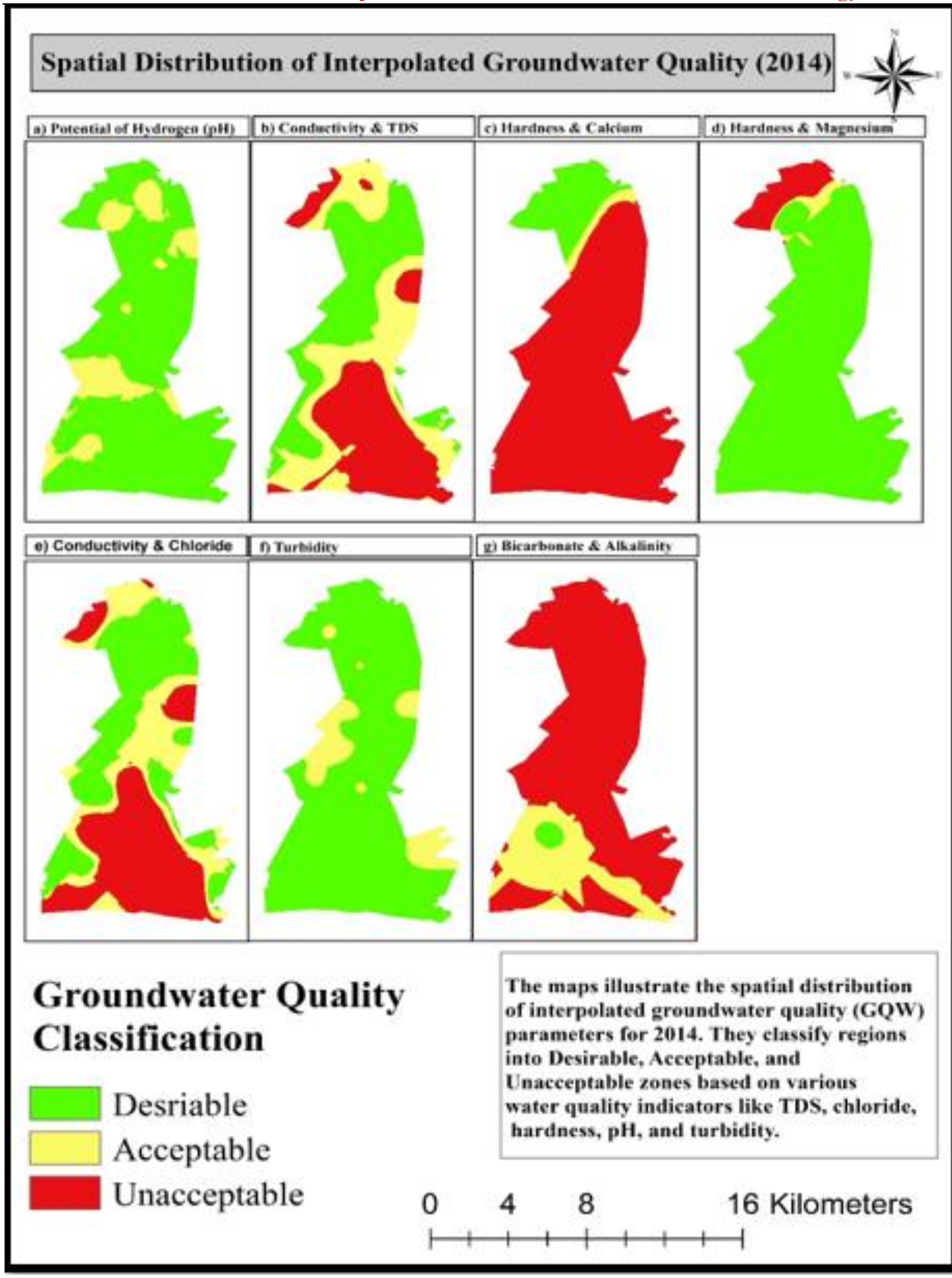

Figure 3. Spatial distribution of groundwater quality (2014) showing desirable, acceptable, and unacceptable zones across key water parameters.

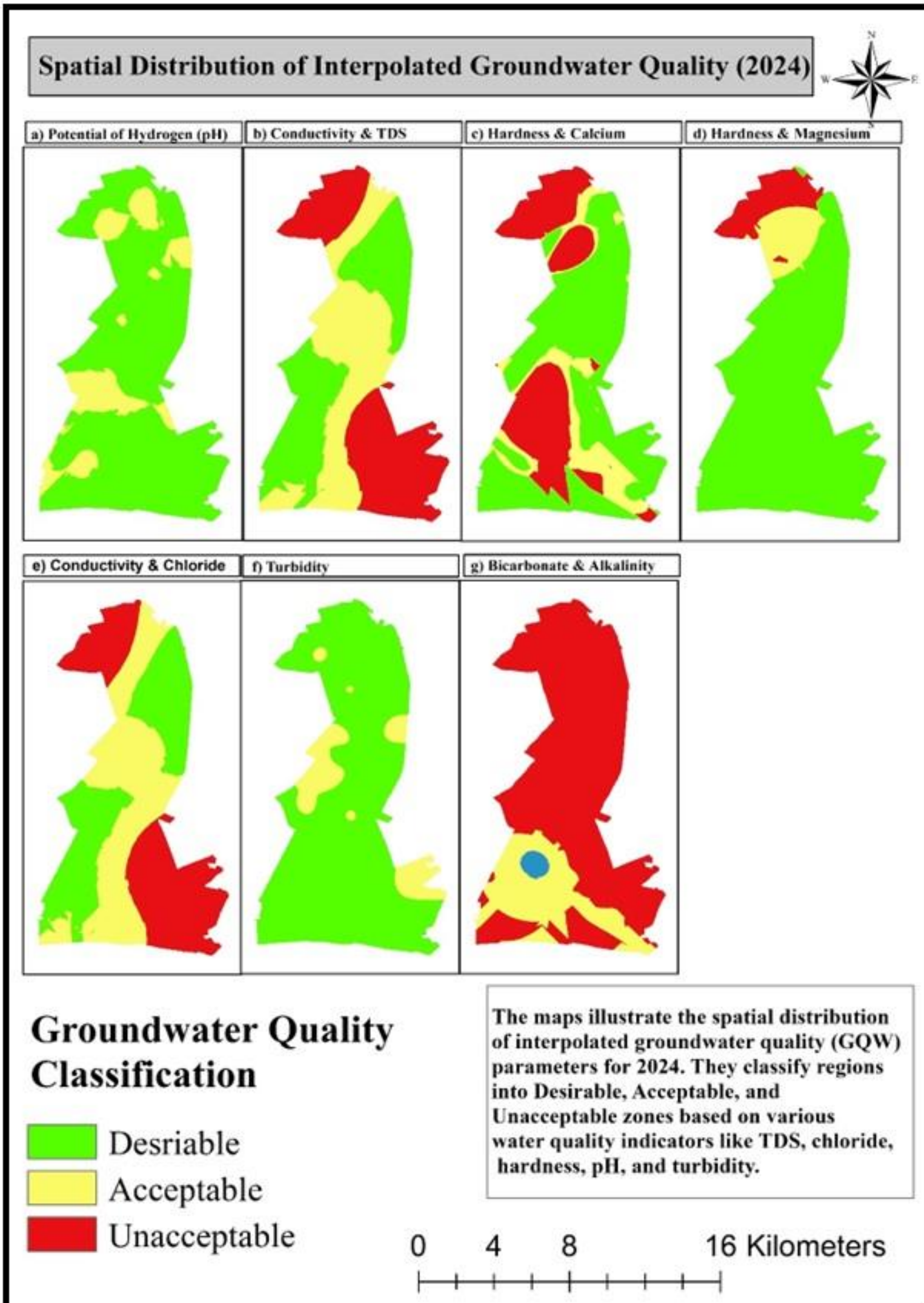

Figure 4. Spatial distribution of groundwater quality (2019) showing desirable, acceptable, and unacceptable zones across key water parameters

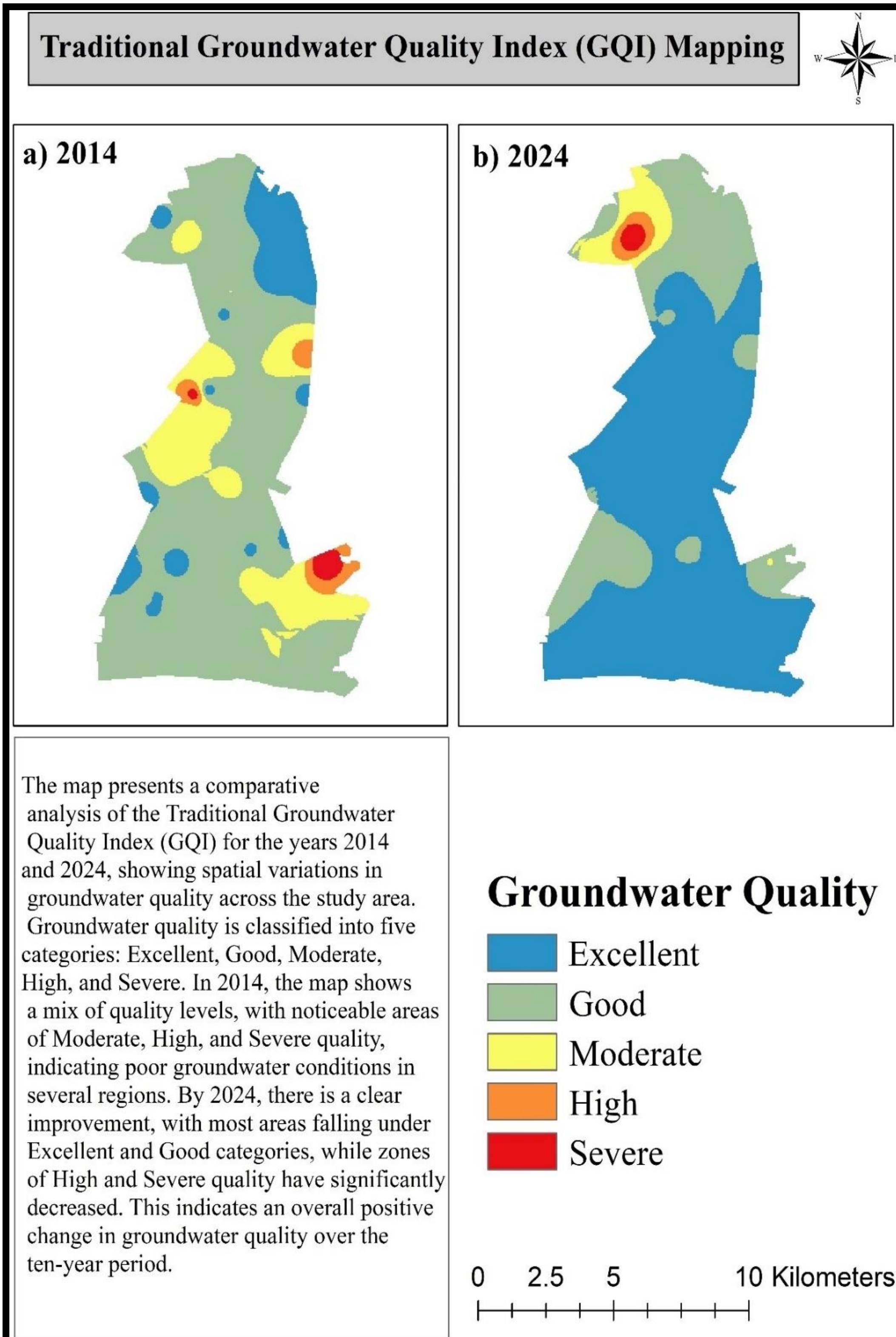

Figure 5. Temporal changes in groundwater quality from 2014 to 2024 based on Traditional GQI maps illustrate deterioration by 2019, followed by significant recovery by 2024.

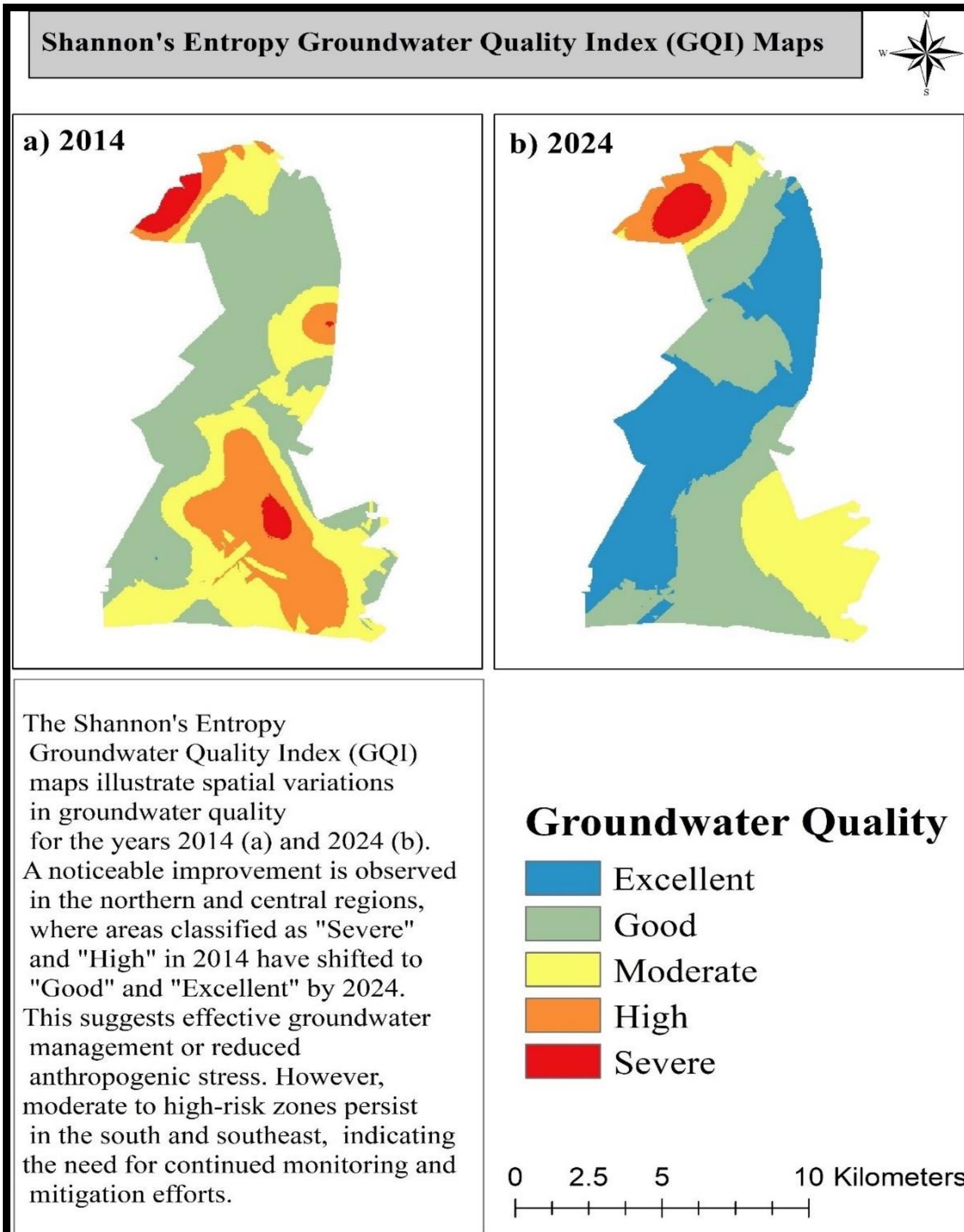

Figure 6. Temporal variations in groundwater quality from 2014 to 2024 using Shannon's Entropy GQI, showing degradation followed by significant improvement.

Conclusion:

This research analyzed groundwater quality in the municipal towns of Gulberg and Nishtar while taking advantage of the latest geospatial and statistical tools in the years 2014 and 2024, through the use of traditional methods and entropy-based water quality index (WQI) models to understand groundwater quality trends. The findings were noticeable for considerable spatial and temporal variations in the water quality variables, including Total Dissolved Solids (TDS), electrical conductivity, calcium, magnesium, hardness, bicarbonate, and turbidity. Indicator Co-Kriging emerged as the best interpolation option where correlated parameters were present, and Kriging was the most appropriate for pH mapping. In contrast, IDW interpolation had limited sites in which it could be applied, and was only applicable for turbidity. The correlation analysis confirmed key parameter dependencies with strong correlations between TDS with EC, and bicarbonate with alkalinity, which added robustness to model selection and spatial predictions. Overall, the study revealed improving groundwater conditions in a number of areas, potentially due to enhanced groundwater management practices, increased public awareness, reduced contamination sources, and improved land use planning.

Credit Declaration:

Abdullah Riaz, Syed Muhammad Usman, Aeman Samad, Muhammad Ilyas: Conceptualization, Methodology, Formal analysis, Writing- original draft. Dr. Muhammad Hamid Chaudhary, Ms. Qudsia Gulzar: Supervision, Conceptualization, Writing- review & editing.

Declaration of Competing Interest:

Authors declare that there is no conflict of interest either financially or as personal relationships that could have inappropriately influenced the work presented in this paper.

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