Geospatial Assessment of Groundwater Quality Using Water Quality Index (WQI) in Bahawalpur (Pakistan)

Awais Munir[1], Syed Naqi Raza[2], Iftikhar Ahmed[3], Asma Majeed[4], Sundas Nazeer[5], Usman Ali[6], Farheen Nazli[7], Zeshan Quddos[8], Anila Anwar[9], Waqas Munir[10] and Hafiza Momina Rafiq[11]

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Abstract

This study assessed groundwater quality in Bahawalpur, Pakistan, using the CCME-WQI method. Geographic Information System (GIS) tools were utilised to facilitate a safe drinking water evaluation. The groundwater in the city was sampled and analysed for ten physicochemical properties, including pH, total hardness (TH), total dissolved solids (TDS), electrical conductivity (EC), turbidity (NTU), calcium (Ca), magnesium (Mg), potassium (K), sodium (Na) and Lead (Pb). Seventeen groundwater samples were collected from various locations throughout the city. Analysis showed that groundwater pH levels were within permissible drinking limits, although slightly elevated. However, most samples exceeded acceptable hardness and TDS levels, requiring treatment before use. According to the findings of the CCME-WQI, only 6% of the evaluated regions had exceptional or high water quality, while 82% of the sites had poor water quality. Hamaitian Basti recorded the poorest groundwater quality index. According to the results of the spatial mapping, it was determined that the water quality in the southern and eastern portions of the city was lower. In comparison, the water quality in the northern and western portions of the city was higher. The average WQI of 41 shows inferior groundwater quality in Bahawalpur. Immediate treatment is necessary to ensure safe drinking water for residents.

Keywords: Geospatial Assessment, Groundwater, Water Quality Index.

Introduction

Water, an essential element for all life forms, constitutes a limited portion of Earth's surface. While abundant, only 2.5% of water is freshwater, with the rest being saline. Among the freshwater sources, groundwater plays a crucial role. As a hidden resource, it is vital for various purposes,

[1]*Lecturer, Institute of Agro-Industry and Environment, The Islamia University of Bahawalpur, Pakistan. Corresponding Author Email: awais.munir@iub.edu.pk*
[2]*MS Scholar, Institute of Agro-Industry and Environment, The Islamia University of Bahawalpur, Pakistan.*
[3]*Assistant Professor, Department of Agricultural Engineering, Khawaja Fareed University of Engineering and Information Technology, Rahim Yar khan, Pakistan.*
[4]*Assistant Professor, Institute of Agro-Industry and Environment, The Islamia University of Bahawalpur, Pakistan.*
[5]*Student, Institute of Agro-Industry and Environment, The Islamia University of Bahawalpur, Pakistan.*
[6]*Teaching Assistant, Department of Agricultural Engineering, Khawaja Fareed University of Engineering and Information Technology, Rahim Yar khan, Pakistan.*
[7]*Lecturer, Institute of Agro-Industry and Environment, The Islamia University of Bahawalpur, Pakistan.*
[8]*MS Scholar, Department of Climate Change, Muhammad Nawaz Sharif University of Agriculture, Multan, Pakistan.*
[9]*MS Scholar, Institute of Agro-Industry and Environment, The Islamia University of Bahawalpur, Pakistan.*
[10]*Lecturer, Department of Architecture,,The Islamia University of Bahawalpur, Pakistan.*
[11]*Student, Institute of Agro-Industry and Environment, The Islamia University of Bahawalpur, Pakistan.*

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including drinking, agriculture, and industry (Latif et al., 2024). However, increasing population, climate change, and pollution are threatening the availability and quality of groundwater. In many regions worldwide, including those in South Asia, groundwater serves as a primary source of water. South Asian countries face diverse challenges to groundwater quality due to geological factors, human activities, and contamination. Groundwater contamination with arsenic is a significant issue, affecting millions and causing severe health problems. Pakistan, for instance, is grappling with deteriorating groundwater quality due to urbanisation, industrialisation, and inadequate sanitation (Ali et al., 2024). Water quality assessment relies on parameters such as pH, total hardness, total dissolved solids, and heavy metals. Anwar et al. (2024) demonstrated that GIS and remote sensing are effective for modelling groundwater potential zones. Geographical Information Systems (GIS) and geostatistical methods are pivotal for assessing and mapping groundwater quality. GIS aids in visualising spatial data, while geospatial statistics provide insights into spatial distributions and relationships between variables. Addressing the issue of declining groundwater quality is crucial for public health and sustainable development (Anwar et al., 2024). The research aims to assess the groundwater quality in Bahawalpur City, a region that is heavily reliant on groundwater. By integrating water quality data with GIS tools, the study will provide a comprehensive understanding of the spatial distribution of water quality.

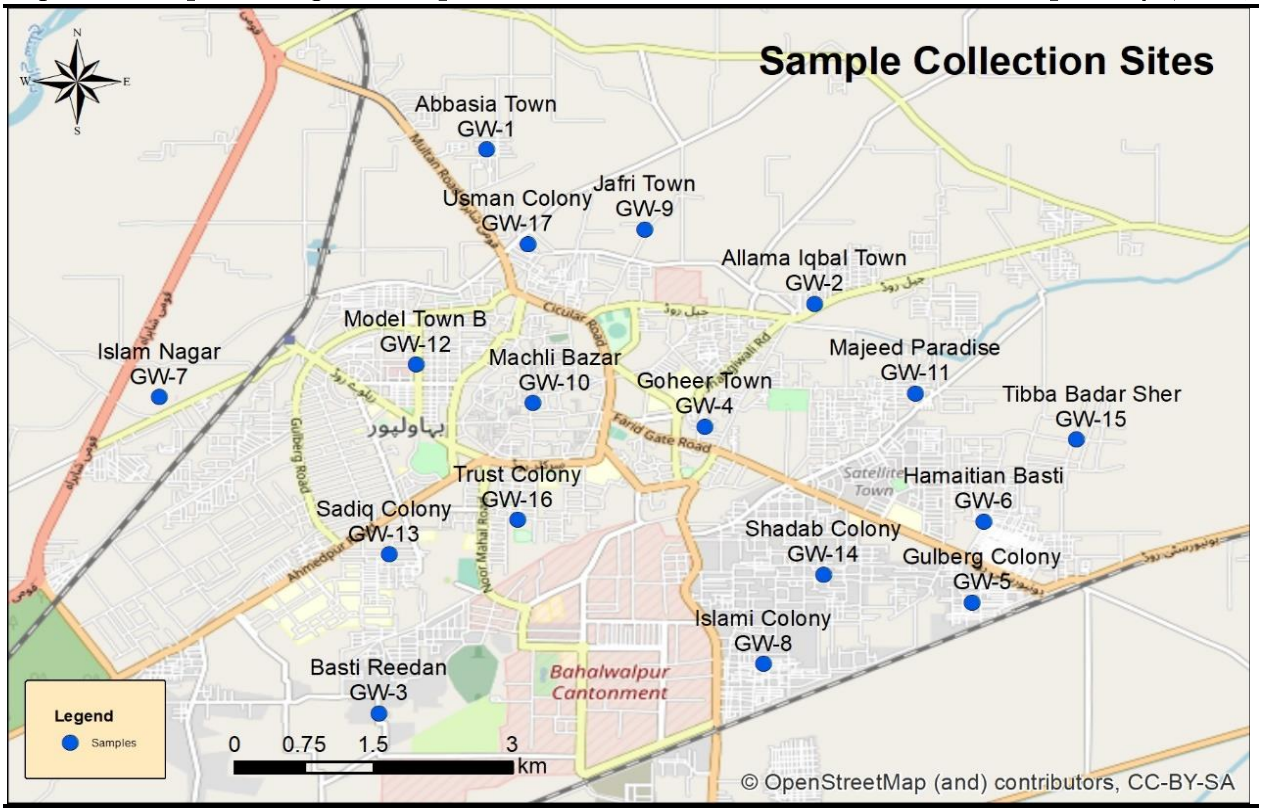
In arid Bahawalpur, groundwater is the primary source for meeting the needs of residential, agricultural, and industrial sectors, due to the scarcity of rainfall and limited surface water resources. It is primarily extracted through hand pumps, shallow wells, and tube wells (Riaz et al., 2018). Excessive groundwater pumping has lowered the water table, causing shortages in parts of Bahawalpur. Pollution from poor waste disposal, agriculture, and industry is further degrading water quality. (Khan et al., 2020). Groundwater in Bahawalpur requires intensive research and monitoring for sustainable management. Multiple pollution sources threaten its quality, putting resources at risk. Agricultural chemicals, including pesticides, herbicides, and fertilisers, significantly contribute to contamination (Rehman et al., 2025). Additionally, using excessive water for irrigation can lead to the accumulation of salts and other chemicals in the soil, which may eventually seep into the groundwater supply. Hafeez et al. (2025) conducted a geospatial analysis to identify floodwater hazard zones in District Muzaffargarh, Pakistan. Rainfall, elevation, and land use/land cover were identified as the most influential factors governing water susceptibility in the study area (Hafeez et al., 2025).

This problem may be circumvented by reducing the quantity of water utilised for irrigation. Industrial activities in Bahawalpur release untreated effluents containing heavy metals and harmful compounds, polluting groundwater. Household and commercial waste further adds to contamination risks. Improper disposal fosters organic buildup and microbial growth, worsening groundwater quality (Rasheed et al., 2014). Improper municipal solid waste disposal in Bahawalpur allows heavy metals, organic matter, and microbes to seep into the groundwater. This contamination poses a threat to the health and overall quality of life of residents (Khan et al., 2020).

Materials and Methods

Groundwater samples were taken from 17 different boreholes in residential neighbourhoods with a high population density. Groundwater samples from 17 boreholes were collected using a 25 x 25 grid system, stored in labelled polypropylene bottles, and geo-referenced using GPS. Each borehole provided separate samples for physical and chemical analysis. The Water Testing Laboratory in Bahawalpur analysed them using APHA standard methods (Rice et al., 2012). The parameters, such as pH, Hard, TDS, EC, NTU, Ca, Mg, K, Na and Pb, were examined using volumetric techniques for testing.

Figure 1: Map showing the samples collected from different sites in Bahawalpur city (n=17)



CCME-WQI Method

F_1 is the scope which shows the disagreement made throughout the interested hour by evaluating the scope to range of water quality rule guideline (Cash & Wright, 2001). It means the number of variables or parameters are unable to meet the standard limit of quality of water.

$$F_1 = \left(\frac{Number\ of\ failed\ variable}{Total\ number\ of\ variable}\right) x\ 100 \qquad 1$$

F_2 is the frequency estimation. It estimates the total frequency of where the standard limit is not matched. It shows the individual tests that do not meet the acceptable limits in percentage.

$$F_2 = \left(\frac{Number\ of\ failed\ test}{Total\ number\ of\ test}\right) x\ 100 \qquad 2$$

The amplitude is increased by donating F_3. It gives an account of the margin by which the test values fall short of their objective (Hurley et al., 2012). The computations are done in three different phases.

$$Excrusion_i = \left(\frac{Failed\ test\ value\ i}{objective\ j}\right) - 1 \qquad 3$$

By adding up the distance that each test deviates from its intended goal and then dividing that amount by the entire number of tests, one may derive the measure of aggregate for the number of tests as a whole that are in conflict with one another. The Normalized Sum of Excursion is the name given to this particular variable (nse) as given below:

$$nse = \left(\frac{\sum_{i-1} n \ Excrusion_i}{number \ of \ tests} \right) \quad 4$$

An asymptotic function that scales the excursion normalised sum from purpose (nse) to generate a value between 0 and 100 is used to calculate F_3, which is the result of the function.

$$F_3 = \left(\frac{nse}{0.01\, nse + 0.01} \right) \quad 5$$

After obtaining all of the components, the record of index may be determined by combining these three factors as vectors together. As a result, the square of the index will be equal to the total of the squares of all of the vectors.

These three factors are mentioned along one axis in a three- dimensional space characterized by the index using this methodology. Therefore, the index may go in directly proportion by changes in all these factors using this model.

The CCME-WQI can be calculated as:

$$CCME - WQI = 100 - \frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732} \quad 6$$

For index scaling from 0 to 100, 1.732 factor has been introduced.

As a result of the fact that the individual components may have values as high as (100), the vector length can reach a maximum value of 1.732, as shown in the following table:

$$\sqrt{100^2 + 100^2 + 100^2 = \sqrt{30{,}000} = 1.732} \quad 7$$

Note that zero value points towards poor water quality, whereas the more value gets closer to 100 the more it signifies water quality excellent (Cash & Wright, 2001).

Table 1: CCME-WQI Values and Categories

Category	CCME-WQI Values
Excellent	95-100
Good	80-94
Fair	60-79
Marginal	45-59
Poor	0-44

Results

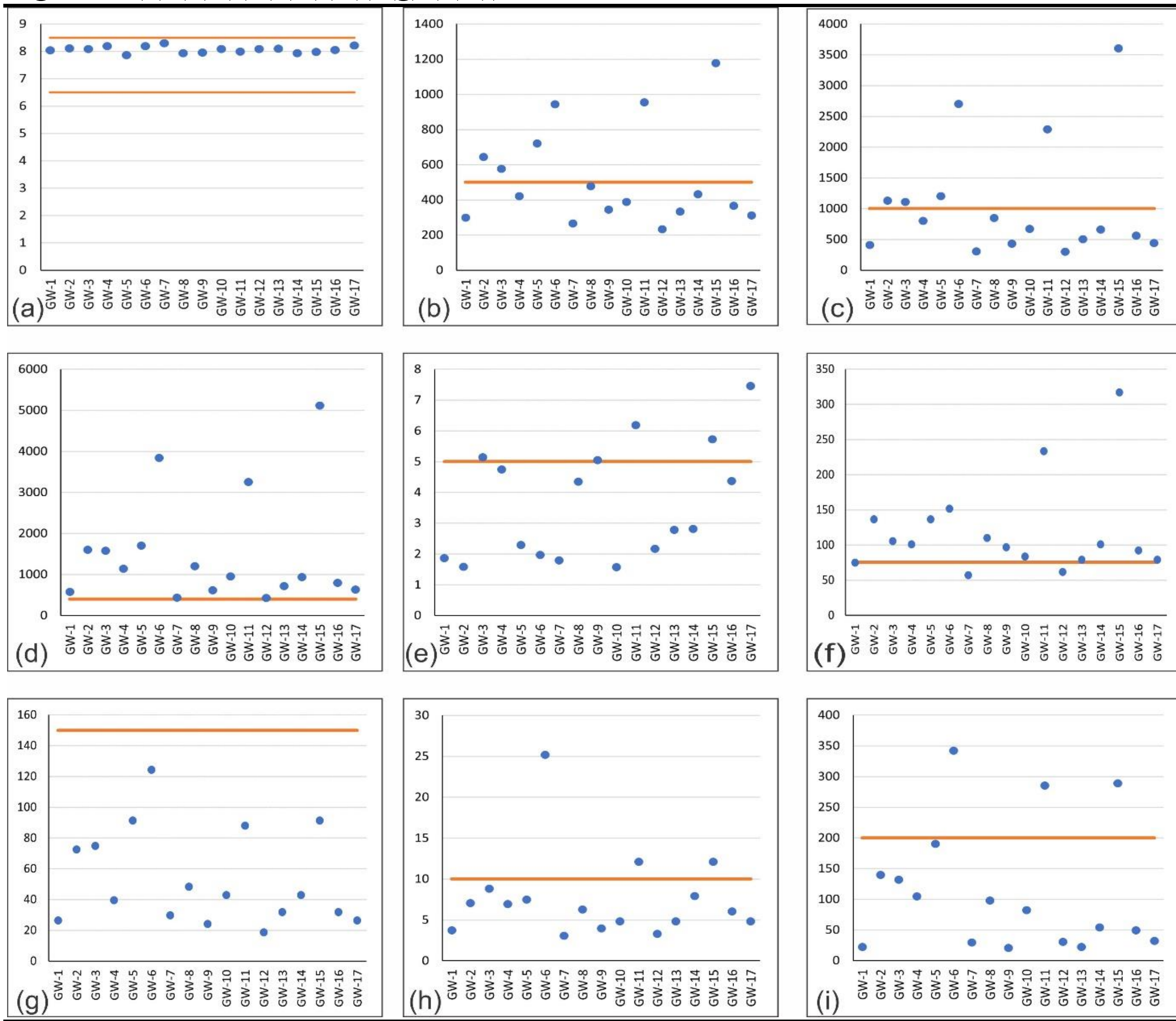
Water quality is crucial for protecting human health and the environment. Its suitability for drinking, irrigation, and industry is assessed by comparing parameters with regulatory standards (Shah et al., 2007). The following parameters are used for making comparisons: pH, Total Hardness (TH), Nephelometric Turbidity Units (NTU), Electrical Conductivity (EC), Calcium (Ca), Magnesium (Mg), Potassium (K), Sodium (Na) and Lead (Pb). Each parameter is assigned a unique standard limit determined by WHO. Suppose the values of these parameters in water samples are higher than the regulatory limits. In that case, this indicates that the water quality is poor and may provide potential human and environmental health hazards. High levels of TDS, EC, and TH in drinking water can cause health issues like digestive disorders and kidney damage. Statistical results and charts help trace pollution sources for mitigation.

Table 2: Descriptive Statistics of Water Quality Parameters (n=17)

Statistics	pH	Hard (ppm)	TDS (ppm)	EC (uS/cm)	Turb. (NTU)	Ca (ppm)	Mg (ppm)	K (ppm)	Na (ppm)	Pb (ppm)
Mean	8.1	523.0	1057.3	1651.9	3.6	118.7	53.3	7.6	154.6	0.004
Median	8.1	421.8	668.8	1045.0	2.8	101.2	42.9	6.3	82.5	0.004
Mode	8.1	-	-	-	-	136.4	26.4	4.8	22.0	0.010
St. Dev.	0.1	276.5	936.7	1463.4	1.9	65.9	31.0	5.3	197.9	0.003
Range	0.4	943.5	3304.4	5163.4	5.9	259.6	105.6	22.1	672.1	0.010
Minimum	7.9	233.1	300.3	468.6	1.6	57.2	18.7	3.1	20.9	0
Maximum	8.3	1176.6	3604.7	5632.0	7.5	316.8	124.3	25.2	693.0	0.010

The Table 2 provides descriptive statistics for ten water quality parameters in Bahawalpur City, with a sample size of n=17. The average pH of water samples in Bahawalpur is 8.1±0.1, with a minimum value of 7.9 and a maximum of 8.3. The standard deviation is 0.1, indicating that the pH values are relatively consistent across the samples. The average hardness value is 523±276.5, ranging from 233.1 to 1176.6. The standard deviation is high, indicating a wide variation in hardness values across the samples. The average TDS value is 1057.3±936.7, with a minimum value of 300.3 and a maximum of 3604.7. The average EC value is 1651.9±1463.4, ranging from 468.6 to 5632.0. The average NTU value is 3.6±1.9, with a minimum of 1.6 and a maximum of 7.5. The standard deviation is relatively low, indicating that NTU values are reasonably consistent across the samples. The average calcium concentration is 118.7±65.9, ranging from 57.2 to 316.8. The standard deviation is moderate, indicating some variation in calcium concentrations across the samples. The average magnesium concentration is 53.3±31.0, ranging from 18.7 to 124.3. The standard deviation is moderate, indicating some variation in magnesium concentrations across the samples. The average potassium concentration is 7.6±5.3, ranging from 3.1 to 25.2. The low standard deviation indicates that the samples' potassium concentrations are relatively consistent. The average sodium concentration is 154.6±197.9, ranging from 20.9 to 693.0. The standard deviation is high, indicating a wide variation in sodium concentrations across the samples.

Figure 2: (a) (b) (c) (d) (e) (f) (g) (h) (i)



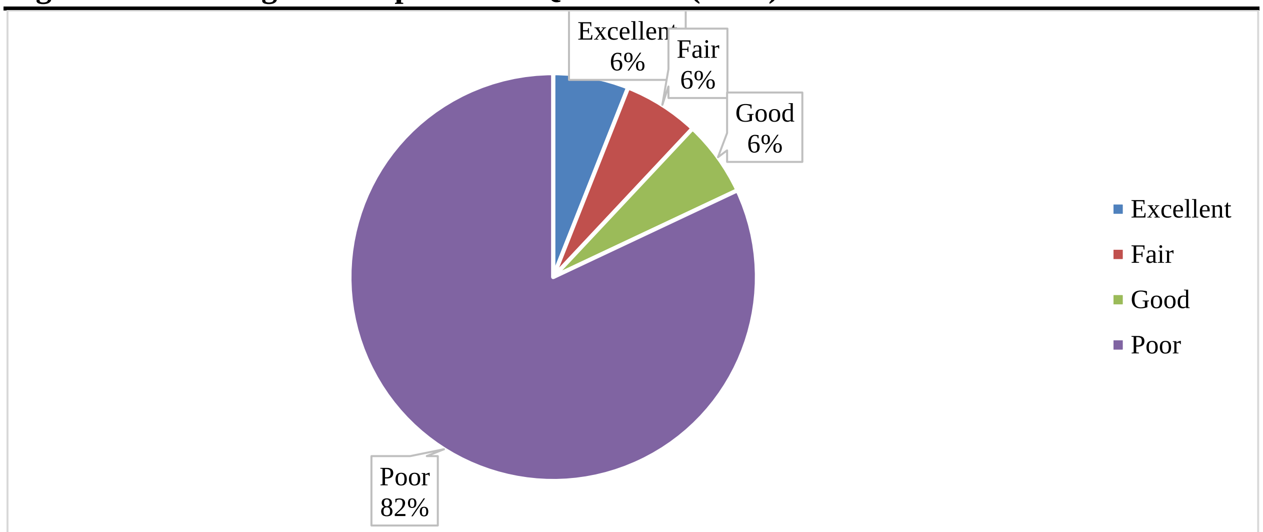
The pH levels of all groundwater samples were slightly over the suggested value but still within the acceptable range for drinking water. Groundwater samples' hardness concentration was above the WHO-permitted limit, suggesting the necessity for treatment to lessen hardness. All but two sites had Total Dissolved Solids (TDS) readings over the allowable limit, suggesting the necessity for treatment or purification before to consumption. Several areas' electrical conductivity (EC) measurements were much greater than the allowable limit, an indicator of poor water quality. All samples' turbidity readings were below the allowable threshold, suggesting that the water is safe to drink. Calcium (Ca) concentrations were greater than the permissible limit in every area, suggesting possible problems with the groundwater's quality. The concentrations of magnesium (Mg) were below the acceptability level, suggesting that the water was safe to consume in terms of Mg content. The majority of sites had potassium (K) concentration that was within acceptable limits, but some did not, necessitating intervention and mitigating measures. The amount of sodium (Na) varied across various places, with some surpassing the permitted limit and others staying inside it. The concentrations of Pb were observed in the groundwater, and all the samples were found within the permissible limits by WHO. Only 14 samples showed the concentrations of lead.

Table 3: Descriptive Statistics of WQI (n=17)

Statistics	Values
Mean	41.1
Median	35.1
Mode	-
St. Dev.	21.4
Range	76.4
Minimum	20.6
Maximum	96.9

The mean WQI was 41.06, indicating overall poor water quality, with a median of 35.07 showing skewness toward lower values. A wide range (20.56–96.93) revealed both very poor and relatively good samples. The high standard deviation (21.37) reflects significant variability in groundwater quality across Bahawalpur.

Figure 3: Percentage of Samples for WQI Results (n=17)



The pie graph in Figure 3 shows the Water Quality Index (WQI) values distribution for the studied locations. Out of 100 locations, the graph indicates that only 6 locations have excellent water quality (6% of the total locations). Similarly, 6 locations have good water quality (6% of the total), and 6 locations have fair water quality (6%). However, the majority of the locations, 82 out of 100 (82% of the total locations), have poor water quality according to the CCME-WQI guidelines. This indicates that a large proportion of the groundwater in the studied areas is suitable for drinking with appropriate treatment.

Table 4: Water Quality Index Results as per CCME Guidelines (n=17)

Code	Location	F1	F2	E	nse	F3	WQI	Categories
GW-1	Abbasia Town	0	0	1.2	1.2	55.25	68	Fair
GW-2	Allama Iqbal T.	33	100	0.7	0.7	41.20	35	Poor
GW-3	Basti Reedan	44	100	0.3	0.3	25.89	35	Poor
GW-4	Goheer Town	11	100	1.5	1.5	59.40	33	Poor
GW-5	Gulberg Colony	33	100	7.6	7.6	88.41	21	Poor
GW-6	Hamaitian Basti	67	100	0.0	0.0	0.00	31	Poor
GW-7	Islam Nagar	0	0	0.5	0.5	31.82	82	Good
GW-8	Islami Colony	11	100	0.3	0.3	23.10	40	Poor
GW-9	Jafri Town	22	100	0.1	0.1	10.29	41	Poor
GW-10	Machli Bazar	11	100	6.2	6.2	86.09	24	Poor
GW-11	Majeed Paradise	78	100	0.0	0.0	0.00	27	Poor
GW-12	Model Town B	0	0	0.1	0.1	5.30	97	Excellent
GW-13	Sadiq Colony	11	100	0.3	0.3	25.89	40	Poor
GW-14	Shadab Colony	11	100	11.4	11.4	91.93	21	Poor
GW-15	Tibba Badar Sher	78	100	0.2	0.2	18.83	26	Poor
GW-16	Trust Colony	11	100	0.5	0.5	35.38	38	Poor
GW-17	Usman Colony	22	100	0.0	0.0	0.00	41	Poor

The findings regarding the Water Quality Index (WQI) according to the recommendations established by the Canadian Council of Ministers of the Environment (CCME) are shown in Table 4, for a number of different sites (coded as GW-1 to GW-17). The table is organised into the following categories: Code, Location, F1 (Scope), F2 (Frequency), Excursion (E), nse, F3 (Amplitude), and CCME-WQI. The CCME-WQI is determined by taking into account these three variables: F1 (Scope), F2 (Frequency), and F3 (Amplitude). F1 represents the percentage of variables that did not meet their objectives at least once during the time period that is being taken into consideration, F2 represents the percentage of individual tests that did not meet objectives, and F3 is calculated based on the collective amount by which individual tests are out of compliance. The value of the CCME-WQI may vary anywhere from 0 to 100, with a higher number indicating greater overall water quality.

The CCME-WQI categorizes water quality as excellent, good, fair, marginal, or poor. Most sites in Bahawalpur showed poor groundwater quality, except Model Town B (GW-12) with an excellent score of 96.9. The lowest score was 20.6 at Gulberg Colony (GW-5), indicating very poor quality. Several locations, including Allama Iqbal Town, Hamaitian Basti, and Shadab Colony, also fell into the poor category.

Table 3 shows groundwater quality in Bahawalpur ranging from poor to fair, with only limited sites meeting safe standards. WHO recommends WQI >90 for good quality, while the U.S. EPA sets 50 as the acceptable limit. Only Model Town B (GW-12) meets WHO's guideline, while Islam Nagar (GW-7) and Sadiq Colony (GW-13) fall into the "Good" category but below EPA's standard. Most other sites remain in the poor or fair range, requiring treatment before drinking.

GIS mapping was used to visualize WQI values in Bahawalpur through choropleth and heat maps, highlighting spatial water quality variations. Based on CCME-WQI, one site (Islam Nagar, GW-7) showed good quality, two sites (Abbasia Town, GW-1; Gulberg Colony, GW-5) were fair, and 14 sites were poor. Hamaitian Basti (GW-6) had the worst quality with a WQI of zero. Overall, northern and eastern parts showed poorer groundwater quality compared to the southern and western areas.

Figure 4: Spatial distribution of CCME-WQI in Bahawalpur City (n = 17)

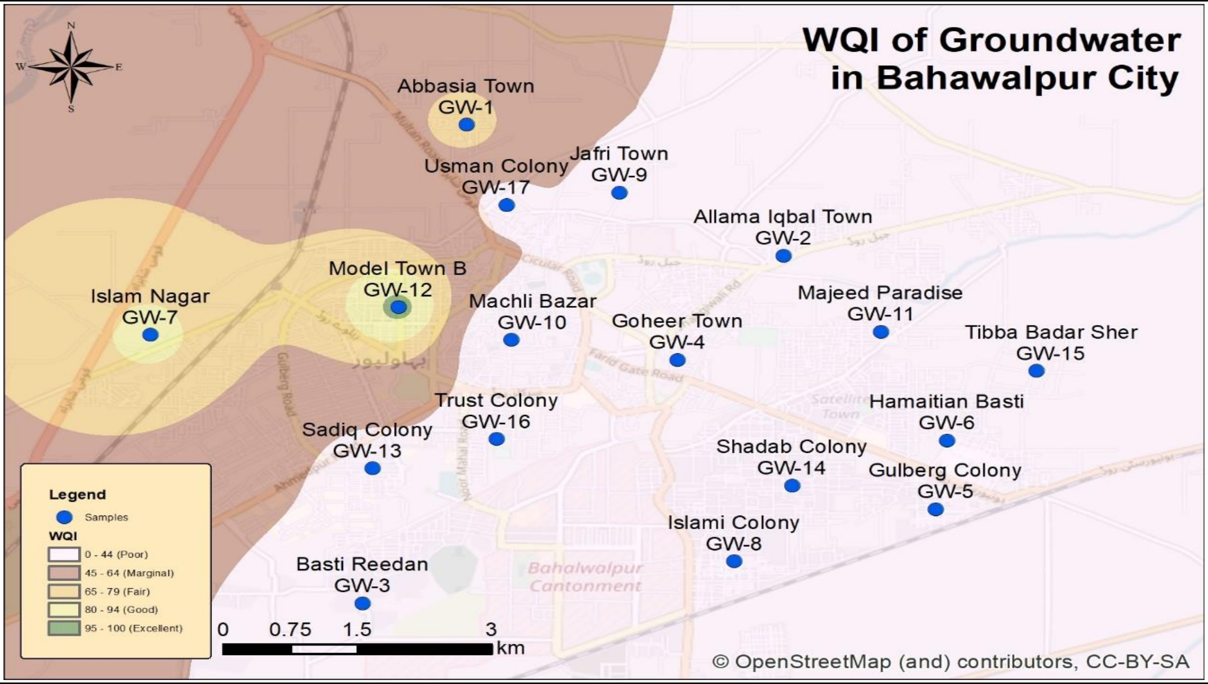


Table 5: Pearson Correlation Matrix of Groundwater Quality Parameters (n=17)

	pH	*Hard*	*TDS*	*EC*	*NTU*	*Ca*	*Mg*	*K*	*Na*	*Pb*
pH	1									
Hard	-0.27	1								
TDS	-0.17	0.97	1							
EC	-0.17	0.97	1	1						
NTU	-0.08	0.22	0.24	0.24	1					
Ca	-0.35	0.93	0.93	0.93	0.38	1				
Mg	-0.17	0.91	0.85	0.85	0.00	0.71	1			
K	0.05	0.77	0.79	0.79	0.03	0.56	0.86	1		
Na	-0.12	0.95	0.99	0.99	0.20	0.90	0.84	0.81	1	
Pb	-0.03	-0.18	-0.18	-0.18	-0.32	-0.17	-0.15	-0.21	-0.21	1

Table 5 shows that there is a strong positive correlation between several parameters, such as total dissolved solids (TDS), electrical conductivity (EC), calcium (Ca), and magnesium (Mg). These parameters are all related to the mineral content of the water. Similarly, there is a strong positive correlation between sodium (Na) and TDS/EC, which suggests that the sodium content of the water is also related to its mineral content. On the other hand, there is a negative correlation between pH and hardness, which suggests that as pH decreases, the hardness of the water increases. There is also a weak positive correlation between turbidity (NTU) and some parameters, such as calcium and sodium. There is a weak relationship between Lead and other parameters. The correlation matrix provides useful information about how different water quality parameters are related to each other. It can help identify which parameters may be influencing the overall water quality and can guide further analysis and interpretation of the data. The results of a paired samples test that was carried out on a number of water quality indicators are outlined in Table 5. Each pair illustrates the disparity between the value that was actually measured and the value that is suggested by the World Health Organization (WHO) for that particular parameter. The table presents a two-tailed test's t-value, degrees of freedom, and significance level, as well as the mean, standard deviation, standard error mean, and 95% confidence interval for the difference between each pair.

The pH value showed a significant difference from the WHO recommended value, with a mean difference of 1.07059 and a p-value of 0.000. This indicated that the measured pH value was significantly higher than the WHO recommended value. The hardness and total dissolved solids (TDS) values did not show significant differences from the WHO recommended values, with p-values of 0.735 and 0.804, respectively. The electrical conductivity (EC) value showed a marginally significant difference from the WHO recommended value, with a p-value of 0.062. This indicates that the measured EC value was slightly lower than the WHO recommended value. The turbidity (NTU) value showed a significant difference from the WHO recommended value, with a mean difference of -1.35882 and a p-value of 0.008. This indicates that the measured turbidity value was significantly lower than the WHO recommended value. The calcium (Ca) value showed a significant difference from the WHO recommended value, with a mean difference of 43.64706 and a p-value of 0.015. This indicates that the measured calcium value was significantly higher than the WHO recommended value. The magnesium (Mg) value showed a significant difference from the WHO recommended value, with a mean difference of -96.76471 and a p-value of 0.000. This indicates that the measured magnesium value was significantly lower than the WHO recommended value. The potassium (K) and sodium (Na) values do not show significant differences from the WHO recommended values, with p-values of 0.069 and 0.359, respectively. Lead (Pb) showed a significant difference as p-value of 0.000. WQI showed no significant difference as the p-value was 0.104.

The Table 7 shows the results of a one-sample t-test conducted on the water quality index (WQI) of Bahawalpur city. The test compares the mean WQI value of the sample (41.07) to the hypothetical test value of 50. The results indicate that the mean WQI value is significantly different from 0, with a t-value of 7.92 and a p-value of 0.000. This suggests that the water quality in Bahawalpur city is significantly different from the ideal or standard value of 50, which is the value of WQI that represents the best possible water quality. The 95% confidence interval of the difference between the mean WQI value and the hypothetical test value is between 30.08 and 52.05. Therefore, based on the results of this test, it can be inferred that the overall water quality in Bahawalpur city is not ideal and needs improvement.

Table 6: T-Test of Water Quality Parameters with WHO Standards and WQI with Threshold (n=17)

Pair Differences	Mean	Std. Deviation	Std. Error Mean	t	Sig. (2-tailed)
pH - pH-WHO	1.1	0.1	0.0	38.053	.000
Hard - Hard-WHO	23.1	276.7	67.1	0.345	.735
TDS - TDS-WHO	57.3	936.8	227.2	0.252	.804
EC - EC-WHO	-648.2	1330.4	322.7	-2.009	.062
NTU - NTU-WHO	-1.4	1.8	0.4	-3.035	.008
Ca - Ca-WHO	43.6	65.9	16.0	2.732	.015

Mg - Mg-WHO	-96.8	30.9	7.5	-12.903	.000
K - K-WHO	-2.5	5.2	1.3	-1.946	.069
Na - Na-WHO	-45.3	197.8	48.0	-0.944	.359
Pb - Pb-WHO	-0.043	0.010	0.002	-17.466	.000
WQI - WQI-Threshold	-8.9	21.4	5.2	-1.723	.104

Table 7: One Sample T-Test of WQI in Bahawalpur city (n=17)

One Sample T-Test	t	df	Sig. (2-tailed)	Mean Difference
WQI	7.927	16	0.000	41.0

Discussion

GIS was utilised in this study to assess the physicochemical state of groundwater in Bahawalpur City and to determine the water quality index. The initial objective of this study was to investigate the physicochemical parameters of the groundwater in Bahawalpur City. These parameters refer to the water's chemical and physical properties, respectively. The second study topic is to analyse the groundwater's water quality index in Bahawalpur City. This index indicates the water's overall quality; therefore, its status might provide insight into its quality. The third and final research objective was to evaluate, using GIS, the geographical distribution of the groundwater quality index in Bahawalpur City. This was significant for understanding how groundwater quality varies across different locations. The study's objectives, which align with the research questions, are to examine the physicochemical parameters of groundwater in Bahawalpur City, determine the water quality index, and spatially distribute the groundwater quality index using GIS. These were just a few of the study's goals. The purpose of this study was to provide a comprehensive understanding of groundwater quality in Bahawalpur City, which can inform decision-making and management strategies for groundwater resources in the region. This was accomplished by meeting the objectives mentioned earlier.

The research findings provide significant insight into the nature of groundwater in the region under investigation. Based on the findings, the groundwater in the region under investigation is typically complex. It is not fit for human consumption unless it is first treated to make it softer. In addition, the TDS values in all locations, except Abbasia Town (GW-1) and Islam Nagar (GW-7), exceed the allowable limit, suggesting that the groundwater in these areas may not be suitable for consumption or other domestic purposes unless it is treated or purified first. Abbasia Town (GW-1) and Islam Nagar (GW-7) are the only exceptions to this rule. In a similar vein, the EC readings in certain areas are substantially higher than the allowed limit, indicating the water's poor quality. The study results also indicated that the pH values of the groundwater samples collected from all 17 locations were within the permissible range. However, the average pH value was slightly higher than the recommended value by the WHO. The results also suggested that Ca levels in some locations may exceed the admissibility limit. In contrast, Mg concentrations in all locations were below the admissibility limit set by the WHO. The K content in most locations was within the permissible limit, but some locations require attention and mitigation measures to ensure safe groundwater consumption.

In summary, the study results address the research questions and objectives by providing detailed information on groundwater quality in the study area. The results can be utilised by policymakers, water resource managers, and other stakeholders to develop effective strategies and interventions that ensure safe and clean drinking water for the study area's residents. The study's findings suggested that the groundwater quality in the study area is only suitable for consumption with treatment and purification. The pH values of the groundwater samples are within acceptable limits for drinking water purposes, but the hardness concentration exceeds the permissible limit set by the WHO. The TDS and EC values of the groundwater samples also exceed the permissible limits in most locations, indicating poor water quality. While turbidity levels are within the acceptable limit, Ca and K levels exceed the admissibility limits in some locations. Na levels also exceed the permissible limit in some locations. The results suggest there may be issues with the groundwater quality in the study area, indicating a need for further investigation and measures to ensure the safe consumption of groundwater.

Several studies have been conducted on groundwater quality in Bahawalpur City and other similar contexts. A study by Khan et al. (2020) analysed the groundwater quality in Bahawalpur City and found it was highly contaminated with various pollutants, including nitrates, sulphates, and chlorides. The study attributed the contamination to poor agricultural practices and inadequate wastewater management systems. Another study, conducted in 2017, focused on the arsenic contamination of groundwater in Bahawalpur City and found that nearly 70% of the wells tested had arsenic levels exceeding the safe limit set by the World Health Organisation (WHO). The study recommended implementing measures to control arsenic contamination, including the use of arsenic removal technologies. Suthar et al. (2019) investigated the groundwater quality in the Tharparkar District of Pakistan, which shares similarities with the geography and climate of Bahawalpur City. The study found that the groundwater in the area was highly contaminated with various pollutants, including arsenic, fluoride, and nitrate. The study recommended adopting sustainable water management practices to mitigate contamination. A study conducted by Shah and Joshi (2017) in the Indian state of Gujarat found that the groundwater in the region was contaminated with fluoride and salinity. The study recommended implementing measures to prevent contamination and provide safe drinking water to the local population. These studies highlight the widespread issue of groundwater contamination in many parts of South Asia, including Bahawalpur City, and the urgent need for sustainable water management practices to address this problem.

PCRWR found high levels of arsenic, fluoride, and nitrate in Bahawalpur groundwater, posing health risks such as fluorosis, arsenic poisoning, and methemoglobinemia (Imran et al., 2016). Agricultural areas also showed pesticide contamination (Riaz et al., 2018). Poor wastewater management, waste disposal, and industrial discharges worsen groundwater pollution. Past studies have confirmed rapid groundwater deterioration due to population growth, toxic seepage, and industrialisation (Mehmood et al., 2012; Mohsin et al., 2019).

According to Mohsin et al. (2013), the situation is far worse in the Islamic colony, where 48%, 55%, and 41% of inhabitants had diluted, brackish water with a little odour. The presence of considerable pollution in groundwater was also revealed by laboratory testing of water characteristics. Parameters such as EC, TDS, hardness, pH, and others were significantly beyond the allowed limits set by the WHO. The water was of such low quality that it led to severe waterborne infections, including cholera and dysentery. It was also stated by Rasheed et al. (2014) that the quality of sewage effluents and canal water used for irrigation purposes could have been improved, and the concentration of heavy metals exceeded the safe limits established for optimal water usage. The study recommends regular water quality monitoring, the establishment of additional filtration plants in densely populated areas, and collaborative public-private efforts for improved water management. Urgent action from the district government is necessary to address the poor quality of drinking water. Groundwater deterioration is driven by population growth, waste mismanagement, toxic seepage, and industrial expansion. The findings of the previous studies have also revealed that the physicochemical parameters of groundwater, such as EC, TDS, hardness, pH, calcium, chloride, potassium, sodium, sulphate, nitrate, arsenic, and iron, were significantly above the permissible limits in many areas of Bahawalpur city. These parameters include calcium, chloride, potassium, sodium, sulphate, nitrate, and arsenic (Khan et al., 2020; Mehmood et al., 2012; Riaz et al., 2018).

The study utilised the WQI to assess groundwater in Bahawalpur, revealing values ranging from 56.8 to 86.6, which are mostly unfit for drinking. Many physicochemical parameters exceeded safe limits, confirming earlier findings of poor quality. Suggested solutions include frequent monitoring, additional filtration plants, and public-private partnerships for the provision of clean water. Previous research on the quality of the groundwater in Bahawalpur identified several different physicochemical parameters, including colour, odour, electrical conductivity (EC), total dissolved salts (TDS), alkalinity, hardness, dissolved oxygen (DO), pH, Cl-, F-, NO3-, SO4-2, essential metals (Na, K, Ca, and Mg), and heavy metals. The information you provided was used in these studies (Fe, Ni, Cr, As, Pb) (Imran et al., 2016). According to the findings of these investigations, some of the calculated parameters fell within the acceptable limitations established by the World Health Organisation (WHO) and the Pakistan Standards and Quality Control Authority (PSQCA), while others exceeded these limits. Investigations revealed the presence of high levels of coliform bacteria, arsenic, and iron in the groundwater, which worsens its quality. This contamination contributes to waterborne diseases, such as cholera and diarrhoea. Khan et al. (2020) recommended regular monitoring, more filtration plants, and stricter control of industrial discharges.

Conclusion

The study aimed to assess the water quality of groundwater in Bahawalpur City using physicochemical parameters and the Water Quality Index (WQI). The findings revealed that while the pH levels and turbidity of the groundwater were within acceptable limits, other parameters such as hardness, Total Dissolved Solids (TDS), and electrical conductivity (EC) indicated poor water quality. Additionally, high concentrations of calcium and variations in sodium levels were observed. The spatial distribution of water quality revealed that the northern and eastern parts of the city had poorer water quality compared to the southern and western areas. The study's limitations included a small sample size, a focus solely on physicochemical parameters, and the absence of microbiological analysis. Future research should consider increasing the sample size, including microbial parameters, and identifying sources of contamination. Regular monitoring, public awareness campaigns, and targeted interventions are crucial for enhancing water quality in Bahawalpur City. The study highlights GIS as a vital tool for groundwater quality assessment in Bahawalpur. It provides a foundation for future research and interventions aimed at addressing water issues. Prioritising monitoring, awareness, and collaborative efforts is crucial to safeguard public health.

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