Integrated Source Tracking and Assessment of Drinking Water Contamination in Rural Sindh, Pakistan

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Citation | Ali. A, Keerio. J. A, Abbas. M, Ahmed. A, "Integrated Source Tracking and Assessment of Drinking Water Contamination in Rural Sindh, Pakistan", IJIST, Vol. 8 Issue. 5 pp 2211-2224, August 2026

DOI | https://doi.org/10.33411/IJIST/1967

Received | July 22, 2026 **Revised |** Aug 18, 2026 **Accepted |** Aug 21, 2026 **Published |** Aug 23, 2026.

Introduction/Importance of Study: Water is essential for life, and it can be contaminated by physical, chemical, and biological pollutants. This polluted water can impact human health and lead to abdominal pain, diabetes, diarrhea, and cancers (kidney, liver, and lungs).

Novelty statement: Therefore, a thorough water quality assessment of Khairpur city is done in this study by integrating detailed physicochemical characterization with mathematical modeling. Beyond evaluating the current groundwater status, the developed models were calibrated and validated to accurately predict groundwater quality, offering a robust decision-support framework for sustainable water resource management and future monitoring.

Material and Method: For this, 58 samples were collected according to the major residential areas of the city. Whereas mathematical modeling was done by using WQI and SPI mathematical tools.

Result and Discussion: The analysis showed that all water samples complied with the WHO permissible pH range, while 19 of 58 samples (32.8%) exceeded the WHO limit for total dissolved solids (TDS). Temperature remained within acceptable limits at all sampling locations. Turbidity exceeded the WHO guideline (5 NTU) in 5 samples (8.6%), dissolved oxygen (DO) was below the recommended level in 10 samples (17.2%), and arsenic concentrations exceeded the permissible limit in 9 samples (15.5%). The Water Quality Index (WQI) classified 1 location (1.7%) as excellent, 26 (44.8%) as good, 24 (41.4%) as poor, and 3 (5.2%) as very poor. Similarly, the Synthetic Pollution Index (SPI) identified 25 locations (43.1%) as suitable, 1 (1.7%) as slightly contaminated, 27 (46.6%) as moderately contaminated, 2 (3.4%) as highly contaminated, and 3 (5.2%) as unsuitable for drinking. A strong positive agreement between the WQI and SPI models was observed, with a coefficient of determination (R^2) of 0.78, indicating the reliability and consistency of both assessment approaches.

Concluding Remarks: This study has revealed a minor violation of WHO water quality standards. However, the required thresholds have been achieved at the most of the study locations.

Keywords: Physio-Chemical Analysis; Mathematical Models; WHO Standards; Khairpur City and Arsenic.

Introduction:

The water is fundamental commodity of life for all living species and considered as the key factor for the socioeconomic development of the world [1]. Water has an extraordinary impact on the development of ecosystems. However, various factors such as climate change, global warming, deforestation, population growth, poor management, and rapid urbanization have resulted in a scarcity of drinkable water. These elements may be considered the primary reasons for the decline in environmental quality and the shortage of potable water.

Water is employed for various purposes, so we require it for drinking, industrial use, irrigation, swimming and fishing, among others. Drinking water is described as water mainly meant for human consumption but also serves other household needs. A Person needs approximately 3.785 (liter) /day for drinking [2]. However, the major sources for drinking water are ground and surface water. These sources mainly consist of ground water aquifers, ponds, rivers, reservoirs, and the lakes [3]. The literature states that humans are exposed to drinking water contaminants through direct consumption and indirect ingestion via food and beverages prepared with water [4].

The per capita availability of drinking water has significantly reduced and reached to 1000 cubic meter in 2010, despite referred as having the fourth largest ground water reservoir and blessed with largest irrigation systems [5]. Furthmore, it is impacting the individual water availability caused by the inadequate management and rising population [6].

A study has reported that the drinking water contamination vulnerability causing the serious threat to around 100 million and the 785 million people in Pakistan and globally, respectively [5]. Due to this menace, around 70% population of Pakistan consuming the contaminated water and this causes the waterborne diseases approximately 53,000 children each year aging below five year reported by the United Nations International Children's Emergency Fund (UNICEF) [7]. This contamination mainly happens due to the unchecked human activities, excessive performance of natural processes, unplanned extraction activities and the rapid deterioration of aquifers and their depletion [8]. A study has revealed that the excessive pumping of the groundwater poses the health risks by increasing the exposure to heavy metals such as sodium, flourides, magnesium, calcium and even threatens the soil fertility and its yield [8]. Importantly, WHO (2023) report pointed out that more than 50,000 death cases have been reported due to the diarrhea each year with challenges to deal typhoid, cholera, dysentery, and polio [9]. Although, the lowest concentration of metals such as Ni, Pb, Cr, Cd, and as causes the severe health [10]. Ultimately, these problems get accumulate and resulted in 40% deaths and the 50% of the diseases merely in Pakistan in one in each five people by consuming the substandard drinking water, a staggering 50% of diseases and 40% of deaths are associated with the consumption of subpar water, affecting one in every five individuals [11]. Another study has revealed that these heavy metal causes the apoptosis, cell growth, disturbance in metabolism, and the damage to the antioxidant defense mechanisms [12]. The severity of exposure of As reported in lungs, skin, kidney, bladder and other organ cancer [12].

Therefore, it is strongly recommended that a regular analysis of water is essential for comparing the levels of essential parameters to the desired and permissible level as given in the guidelines of according to US Environmental Protection Agency (USEPA), as given below in Table 1 [13]. For this, a thorough study is being conducted to analyze the drinking water quality and identify the hotspot areas where the recommended levels are violated. Furthermore, the results of the study have been predicted by using the water quality models.

Traditional water quality assessment studies have primarily relied on physicochemical analyses and laboratory-based measurements to evaluate the suitability of drinking water. Although these approaches provide reliable information on water quality status, they often fail to capture the broader dimensions of water resource management, including public water-use practices, spatial variability, and comprehensive pollution assessment. In response to recent advances in environmental monitoring, geospatial technologies, and data-driven assessment methods, the present study adopts an integrated framework that combines household water-use behavior, standardized water sampling and laboratory analysis in accordance with internationally accepted engineering protocols, and quantitative validation using two widely recognized water quality assessment models: the Synthetic Pollution Index (SPI) and Water Quality Index (WQI). The integration of these complementary approaches provides a more robust evaluation of drinking water quality by linking physicochemical characteristics with human water-use patterns and validated pollution indices, thereby enhancing the reliability and practical applicability of the findings for water resource management and public health decision-making. [14].

Table 1. Concentration of Metals and Other Chemical substances in Potable Water.

Contaminant	Secondary Standard
Aluminum	0.05 to 0.2 mg/L
Chloride	250 mg/L
Color	15 (color units)
Copper	1.0 mg/L
Corrosivity	Noncorrosive
Fluoride	2.0 mg/L
Foaming Agents	0.5 mg/L
Iron	0.3 mg/L
Manganese	0.05 mg/L
Odor	3 threshold odor number
pH	6.5-8.5
Silver	0.10 mg/L
Sulfate	250 mg/L
Total Dissolved Solids	500 mg/L
Zinc	5 mg/L

Material and Methods:

Study Area:

The current research focuses on Khairpur Mir's, an agricultural and industrial city located in Sindh, Pakistan. The city consists of eight union councils. The true location of Khairpur district is in the northern region of Sindh. Additionally, the study zone is a subtropical area, primarily chilly in winter and warm in the summer, as shown in Figure 1. The study area is spread over 15,910 km2 with urban portion of 32.50% [15]. The population of Khairpur is 2.6 Million and the number of households are 0.45 Million [15].

It is reported that around 0.1 to 0.4°C mean temperature soars in Sindh annually along with increasing annual precipitation (+30 to +60 mm) [16]. Whereas, the route cause of the pollution of surface and ground water is reported as the agriculture run-off and the industrial effluents [17].

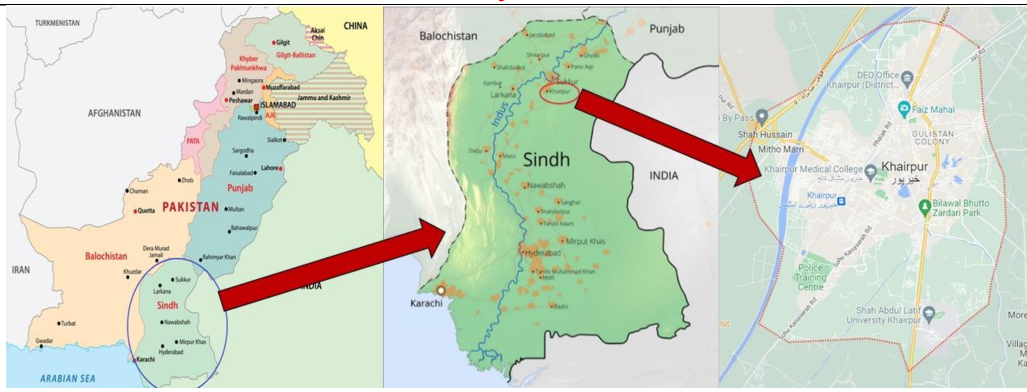

Figure 1. The Google Map of the Study Area

Selection of Sampling Locations:

A total of 58 sampling locations were selected across Khairpur City using a representative spatial sampling approach to ensure comprehensive coverage of the city's drinking water distribution network and groundwater sources, the collection activity of samples is shown in the Figure 2. Sampling points were distributed throughout all major residential, commercial, and peri-urban areas to capture the spatial variability in water quality arising from differences in hydrological conditions, sources of the contamination, water supply schemes, population density, and the land use.

Figure 2. Water Sample Collection from the designated sites.

The sampling locations included areas supplied by different drinking water sources (municipal supply and groundwater), as well as locations with varying distances from the water source and distribution network. The selection of representative sampling locations follows the globally recognized principles for water quality monitoring and assessment. All standard protocols were followed during the collection (collected in 500 ml sterilized bottled), transportation (stored in ice box at the 4°C), and analysis of the samples. The holistic methodology adopted in this research work is presented in Figure 3. Table 2 depicts the suggested allowable range of parameters [18].

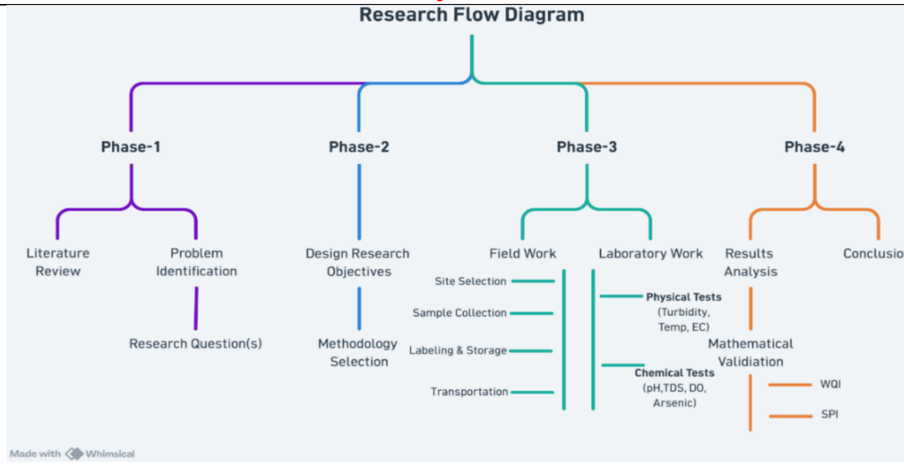

Figure 3. The overall Research Flow Diagram (Prepared in Whimsical AI Tool)

Table 2. Internationally Accepted Drinking Water Standards Provided by WHO.

S. No.	Parameters	WHO Standard
1	Power of Hydrogen (pH)	6.5 - 8.5
2	Turbidity	5 NTU
3	Total Dissolved Solids (TDS)	500 mg/1
4	Electricity conductivity (EC)	400 us/cm
5	Dissolved Oxygen (DO)	5 mg/L
6	Arsenic (As)	0.01 mg/L

The groundwater samples were tested for pH, turbidity, TDS, EC, temperature, arsenic, and (DO), as shown in the Figure 4.

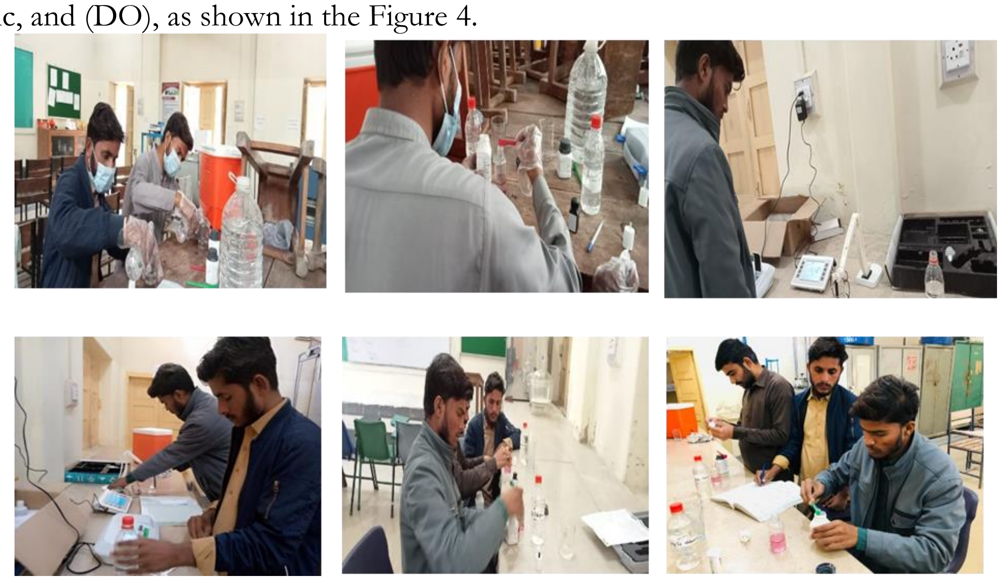

Figure 4. Water Sample Analysis at lab

The results of the analysis were compared to the WHO guidelines. The pH, TDS, EC, DO, and turbidity measurements were carried out using a pH meter, TDS meter, EC meter, DO meter, and turbidity meter, respectively. The Kit technique was utilized to assess arsenic (As) pollution. The methods and the equipment used in this study are listed in the Table 3.

Table 3. Methods and Parameter of Water Quality for Analysis.

Sr:No.	Physical parameters	Method
01	Temperature (celcius °C)	Thermometer
02	Turbidity (NTU)	Turbidity meter
03	Electrical conductivity (EC) (µs/cm)	EC by formula from TDS

Sr:No	Chemical parameters	Method
01	pH	pH meter (Probe method)
02	Dissolved oxygen (DO) (mg/L or ppm)	DO meter (Probe method)
03	Total dissolved solids (TDS) (mg/L or ppm)	TDS meter (Probe method)
04	Arsenic (A S) (mg/L)	Kit method (Probe method)

Result and Discussion:

Chemical Parametric Analysis:

pH:

The study of pH signifies the concentration of Oxygen and the hydrogen ions in any type of water. It scales from 0 to 14 with three different natures; less than 7, equal to 7, and the greater than 7. The results of any water fall below 7 known as the acidic of nature, exactly equal to 7 known as the neutral, and whereas greater than 7 termed as the nature of alkaline. The pH range significantly impacts human health. The U.S. Environmental Protection Agency suggests that pH levels between 6.5 and 8.5 in water are appropriate for drinking.

Figure 5. pH Meter

The digital pH meter (Figure 5) was utilized to measure the pH levels of the gathered samples. pH meters were calibrated using a buffer solution. The glass electrode was rinsed with distilled water and subsequently placed in the beaker containing the water sample, with measurements recorded until the water stabilized at a specific value.

Figure 6 shows the pH values of 58 water samples collected from various locations within the study area are presented. The pH values in the study area were found to have a minimum of 6.3, a maximum of 8.5, and a mean of 7.44.

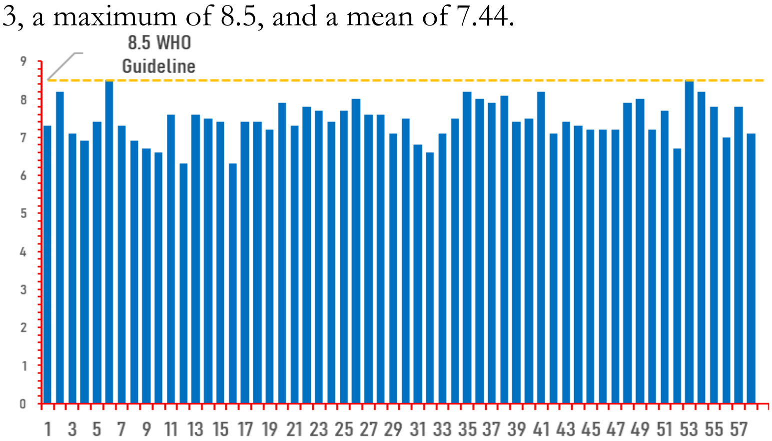

Figure 6. Graphical Representation of pH Results.

The above figure clearly indicates that the pH of all gathered samples falls within the limits set by WHO. Therefore, the water quality in Khairpur city, according to pH analysis, is appropriate for drinking.

Total Dissolved Solids (TDS):

According to the WHO, the portable water should not have a TDS of more the 500mg/l. The assessed TDS readings from 58 various sites in Khairpur City are presented below. The determined minimum, maximum, and average values of total dissolved solids in the study region were 110 mg/L, 3850 mg/L, and 1149.82 mg/L, respectively as shown in the Figure 7.

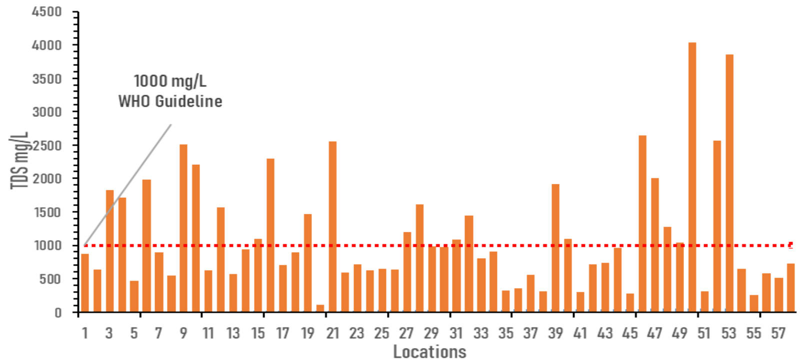

Figure 7. Graphical Representation of TDS Results.

Dissolved Oxygen (DO):

The D.O of water can vary based on the water source; typically, raw water has a lower temperature, and as it undergoes chemical and biological treatment, the D.O concentration may decrease, which can also occur within the water supply network. A reduction in DO levels in water bodies can facilitate the microbial transformation of nitrate into nitrite and sulfide. The level of ferrous iron in the solution may rise, which can cause high discoloration after the aeration of water. No guideline value for health impact is proposed. Nonetheless, extremely elevated D.O levels might intensify corrosion in metal pipes. According to WHO the standard limit of DO of water is 5mg/l. In the present study the DO was measured with digital DO meter as shown in the Figure 8.

Figure 8. DO meter

The recommended limit for dissolved oxygen in drinking water by the WHO is 5 mg/l. The subsequent Figure 9 shows the Turbidity measurements from different areas of Khairpur city. Figure 9 states the recorded minimum, maximum, and average values of DO were 1, 13.2, and 4.10 mg/l, respectively.

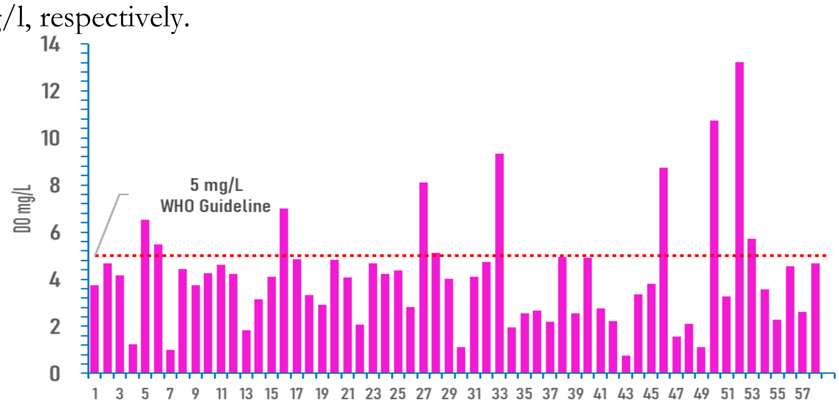

Figure 9. Graphical Representation of DO in the groundwater of the study area.

Arsenic (As):

Arsenic is a naturally found, semi-metal element that is extensively spread throughout the Earth's crust. Arsenic concentrations in the environment may differ by location. Contact with As contamination in drinking water resulted in long-term and cancerous issues. Long-term health consequences consist of stomach pain, black foot disease, diabetes, high blood pressure, intense diarrhea, vomiting, reproductive issues, hindrance of children's mental development, DNA damage, and immune system deficiency. The carcinogenic impacts of as encompass cancer (bladder, kidney, liver, lungs, and skin). As per WHO (World Health Organization), the acceptable level of arsenic in drinking water must be below 0.01 mg/L. In this study, the arsenic concentration in samples was evaluated using the Kit method as shown in the Figure 10.

Figure 10. Arsenic Kit.

The figure below presents the graphical representation of arsenic contamination across various locations in Khairpur city. The World Health Organization recommends a maximum arsenic limit of 0.01 mg/L for safe drinking water and the study area observations as shown in the Figure 11.

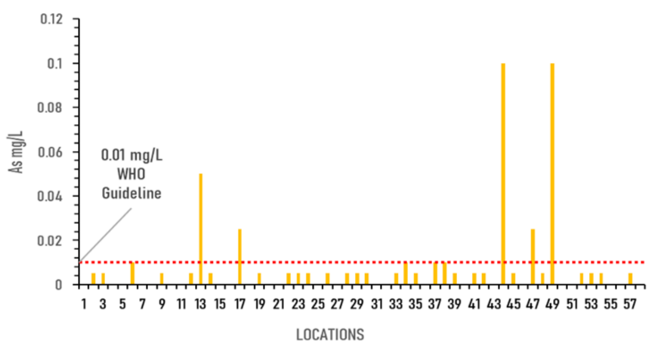

Figure 11. The experimental results of the Arsenic contamination.

Physical Parametric Analysis:

Turbidity:

Turbidity refers to the haziness resulting from a huge quantity of tiny particles. These particles are invisible with the naked eyes. The measurement of turbidity is an important assessment of quality of water. Excessive turbidity is harmful and can lead to health issues. It offers nourishment and housing for pathogens. If not removed, turbidity promotes the return of pathogens in the water supply, leading to outbreaks of waterborne diseases. The WHO guideline for turbidity in drinking water is 5 Nephelometric Turbidity Units (NTU) [18]. Turbidity can range from a muddy river where visibility is absent (high turbidity) to a spring water that appears completely clear (low turbidity). Silt and various colloidal or suspended substances can lead to turbidity. In this study, turbidity was measured using a Digital Turbidity meter (Figure 12).

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Figure 12. Turbidity meter.

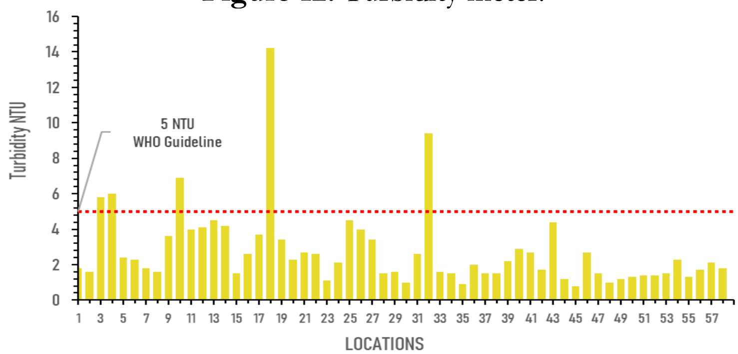

Figure 13. Graphical Representation of Turbidity in the water of the study area.

The recommended turbidity limit for drinking water by the WHO is 5 NTU (Nephlometric Turbidity Unit) [18]. The subsequent Figure 13 depicts the Turbidity values from different sites in Khairpur. The recorded minimum, maximum, and average Turbidity values were 0.8, 14, and 2.77 NTU, respectively. Above Figure 13. represents that most of the samples have turbidity value within limit except 5 samples which are beyond WHO guidelines.

Electrical Conductivity (EC):

The capability of water to conduct electric current is known as electrical conductivity. The level of salt in water is measured by electrical conductivity. Water containing salt and other inorganic substances can carry electric current. Water's conductivity indicates the amount of salts present; therefore, elevated conductivity signifies more saline water. Electrical conductivity correlates with water temperature; as water temperature rises, electrical conductivity also rises. A rise of 1 degree Celsius in water temperature boosts the electrical conductivity of water by 2 to 3%. The measurement unit for electrical conductivity is micro-Siemens per centimeter (µS/cm) or deci Siemens per meter (dS/m). In this study, water sample electrical conductivity was assessed using a formula based on TDS measurements. The WHO recommends a standard limit of EC for drinking water to be 0.75 dS/m or 400 µs/cm.

The figure below displays the graphical representation of Electrical Conductivity at various locations in Khairpur city. The World Health Organization recommends a maximum safe limit of 400 µS/cm of EC for drinking water. The lowest EC value recorded was 55 us/cm, the highest was 2020 us/cm, and the average value stood at 574.91 us/cm.

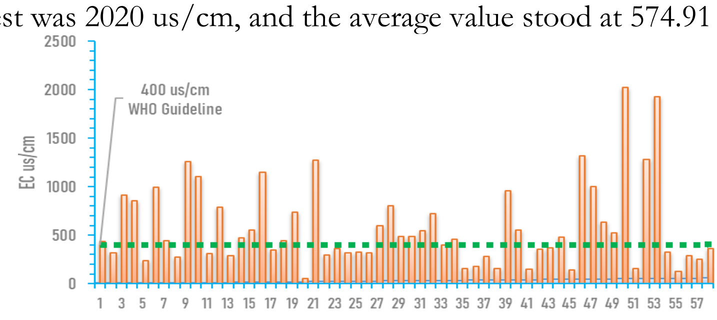

Figure 14. Graphical Representation of Electrical Conductivity in the water of the study area.

The graphical depiction of EC indicates that 31 out of 58 samples have exceeded the suggested value of 0.75 us/cm, as shown in Figure 14. The results indicated that the groundwater quality in Khairpur city is not appropriate for drinking due to its EC levels.

Temperature:

No health-based guidelines exist concerning drinking water temperature, as they don't have a direct link to health. However, it influences chlorination and coagulation efficacy, with its impact on microorganism survival being crucial for health. In this study the temperature of samples was measured with digital thermometer as shown in the Figure 15. The summery of the results achieved in this research are presented in Table 4.

Figure 15. Thermometer.

Table 4. Summary of Water Quality Parameters Analysis Results.

Parameter	pH	TDS mg/L	Turbidity NTU	DO mg/L	EC μs/cm	As mg/L
Permissible	8.5	1000	5	5	400	0.01
Maximum	8.5	3850	14	13.2	2020	0.1
Minimum	6.3	110	0.8	1	55	0
Mean	7.44	1149.82	2.77	4.10	574.91	0.007

Mathematical Modeling:

In current era of computational concepts and establishment of algorithms, the use of mathematical models in any sort of the research is encouraged [19]. Hence, utilizing the analysis findings of various physicochemical parameters mentioned earlier, the quality of groundwater for household purposes was assessed using the SPI and WQI models.

The SPI:

The SPI is a contemporary instrument commonly utilized by various researchers globally to assess the overall quality of water [20]. SPI categorizes water into five distinct groups. Consequently, using measured levels of different physiochemical indicators, the SPI model value for each water sample was determined as follows. The Calculation of the value of constant proportionality (K) was done by using Eq. (1).

$$K = \frac{1}{\sum_{i=1}^{n} \frac{1}{si}} \quad (1)$$

where Si=Permissible concentration of the ith water quality parameter, n =total number of water quality parameters evaluated. Calculating value of relative weight/weight coefficient.

$$Wi = K/Si \quad (2)$$

(Wi) The value Wi can be calculated from Eq. (2).

Calculating value of SPI Finally, the SPI value can be evaluated by using following equation. here D represents the observed value of each analyzed physicochemical parameter.

$$\text{SPI} = \sum_{i=0}^{n} \frac{D}{S} x\, Wi \quad (3)$$

The WQI:

The water quality index (WQI) comes into play, offering a holistic evaluation by considering multiple physicochemical parameters [14]. WQI is recommended as the pivotal tool to determine the quality of water for human consumption and is determined through three steps as indicated in Table 5 [21].

Table 5. Description of the WQI model

Step 1.	Step 2.	Step 3.
Calculation of relative weight (W_i) of the ith parameter using the expression stated as: $$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \quad (3.5)$$ Where w_i is the assigned weight to each of the *ith* water quality parameter.	Calculation of rating scale (Qi): $$Q_i = \frac{C_o}{C_p} \times 100 \quad (3.6)$$ Where C_o is the observed concentration, and C_p is the allowable limit suggested by WHO for domestic use.	Calculation of WQI: $$WQI = \sum W_i \times Q_i \quad (3.7)$$ Using this expression, the overall suitability of water in the study area has been determined.
According to the determined WQI, if WQI <50, water is classified as excellent; >50-100 as good; >100-200 as poor; >200-300 as very poor; and above 300 as unsuitable for drinking [21].		

Utilizing the analysis results of various physicochemical properties mentioned earlier, the quality of groundwater for household purposes was assessed using the SPI and WQI models. To ascertain the WQI model values for each examined water sample, the weights and relative weights assigned to the physicochemical parameters are presented in Table 6.

Table 6. Calculation of Assigned weights, and Relative weight (Wi).

Parameter	WHO Standard	Weight (wi)	Relative weight (Wi)
pH	7	4	0.18
Turbidity	5	3	0.14
DO	50	4	0.18
TDS	500	4	0.18
EC	0.75	4	0.18
As	75	**4**	0.18

Statistical Analysis:

The statistical analysis (SA) of the results was carried out as reported in the literature [20]. The SA shows that the results of pH, DO, and as were in the range of WHO standards. While the EC which is TDS dependent lie in the range of violation of the WHO guidelines. The descriptive statistical analysis of all parameters is given in the below Table 7.

Table 7. The descriptive statistical analysis of the water quality parameters.

Parameter	N	Mean	Median	SD	95% CI Lower	95% CI Upper
Arsenic (mg/L)	58	0.00793	0.00000	0.01924	0.00287	0.01299
Temperature (°C)	58	16.886	16.600	2.340	16.271	17.501
pH	58	7.447	7.500	0.509	7.313	7.580
TDS (ppm)	58	1149.828	910.000	849.822	926.378	1373.277
DO (mg/L)	58	4.100	4.105	2.351	3.482	4.718
Turbidity (NTU)	57	2.744	2.000	2.237	2.150	3.337
EC (µS/cm)	58	574.914	455.000	424.911	463.189	686.639

Where N is the number of the samples, taken in this study.

Regression Analysis of the SPI and WQI Models:

A regression analysis was conducted to correlate the water categories indicated by the WQI and SPI models, establishing a relationship between the two models as reported in the literature for the better understanding [22][23]. The connection indicates a strong correlation between the two models (R^2 = 0.78) as reported in literature [24]. Whereas, this research reported the value of linear coefficient of regression, R^2 is as (0.23). The value for intercept coefficient is (a = -1.02) and value of slope coefficient is (b = 0.014), as presented in Figure 16.

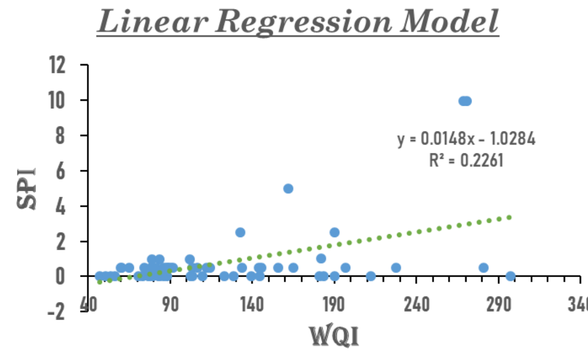

Figure 16. Graphical Representation of linear regression between WQI and SPI models.

Implication of the study:

Pakistan is the 5th largest human population holder in the world [25]. Having the gross domestic product (GDP) and the per capita income which are 2.7% (Fiscal Year 2025) and US$ 1,500 (latest available estimate), classifying Pakistan as a lower-middle-income economy, respectively [26][27]. These two are the major pillars of hinders towards sustainable and adequate as well as for the availability of the safe water to all. Moreover, water challenges persist from poor governance framework, inadequate assessment and the monitoring mechanisms, and the overshadow the considerations of environmental impact assessment (EIA) protocols in every water supply system in Pakistan [28].

Though at present, the water quality is better as per this study reports but the per capita availability is becoming point of the concern. With this growth of population rate (1.6) [29] and declining literacy pertaining to the responsible consumption of water shall pose serious threat in near future. This will threat human health, socioeconomic development, intera-teritory water resources, and for the sustainable environment for better life.

Conclusion:

The present study revealed that the groundwater quality in Khairpur City exhibits considerable spatial variability, with pH remaining within the WHO permissible limits across all sampling locations, indicating acceptable acidity–alkalinity conditions. However, elevated levels of total dissolved solids (TDS), dissolved oxygen (DO), turbidity, and arsenic at several locations indicate localized deterioration in water quality, particularly in groundwater sources. The Water Quality Index (WQI) classified only 2% of the samples as excellent, while 48% were of good quality, 44% were poor, and 11% were very poor, highlighting that nearly half of the sampled locations require water quality improvement before human consumption. Similarly, the Synthetic Pollution Index (SPI) identified only 43% of the samples as suitable for drinking, whereas the remaining samples ranged from slightly to highly contaminated or unsuitable, confirming the presence of significant pollution hotspots. Overall, although the groundwater quality generally complies with WHO standards for certain physicochemical parameters, the elevated TDS and arsenic concentrations in specific areas warrant immediate attention. Therefore, continuous monitoring, appropriate groundwater treatment, and targeted management interventions are recommended to ensure the provision of safe drinking water and to protect public health in the study area.

Acknowledgement: The authors truly acknowledge the generous support from the Prof. Dr. Rasool Bux Mahar (Vice Chancellor, BBS-UTECH, KHP) and the Chairperson of the Civil Engineering Technology Department.

Author's Contribution: Asim Ali: designed and supervised the entire study; Jabir Ali Keerio: looked after the analysis results; Muntazir Abbas: Performed field work; Adeel Ahmed, Worked on the writ-up of the article.

Conflict of interest: Authors exists no conflict of interest for publishing this manuscript in IJIST.

Project details: This research study was conducted as a result of a final year project of the graduating students.

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