Int. J. Econ. Environ. Geol., Vol. 17, Issue 1, 2026, 24-34
Journal home page: www.econ-environ-geol.org

doi: 10.46660/int.j.econ.environ.geol..v17i1.766.

PHYSICOCHEMICAL QUALITY OF GROUNDWATER FOR DRINKING AND IRRIGATION PURPOSES IN UMERKOT DISTRICT, SINDH, PAKISTAN

JAWED BAHADUR ALI, AREEB UL HAQ, ABDUL LATIF QURESHI, NAILA SHAIKH, SAIRA SIDHU* AND NARESH KUMAR GURIRO
U.S.-Pakistan Center for Advanced Studies in Water, Mehran University of Engineering & Technology, Jamshoro, Pakistan

Received: *22 January, 2026* ***Accepted:*** *19 February, 2026*

Abstract: Groundwater is an important source of domestic and irrigation water in arid and semi-arid regions; therefore, its quality must be assessed regularly to ensure safe and sustainable use. This study evaluated groundwater quality in Umerkot District, Sindh, Pakistan, for drinking and irrigation purposes using the Water Quality Index (WQI) and selected irrigation indices. A total of 42 groundwater samples were collected from hand pumps across the study area and analyzed for major physicochemical parameters. WQI was computed using pH, total dissolved solids, calcium, magnesium, sodium, chloride, potassium, and bicarbonate. The results showed that several parameters, including electrical conductivity, pH, total hardness, magnesium, potassium, and sodium exceeded the WHO permissible limits in a considerable number of samples, whereas total dissolved solids, fluoride, sulfate, chloride, bicarbonate, calcium, and arsenic were within permissible limits in most samples. Based on WQI classification, 7% of samples were of good quality, 33% were poor, 38% were very poor, and 21% were unfit for drinking, while no sample fell in the excellent category. For irrigation suitability, groundwater was assessed using soluble sodium percentage, Kelly index, sodium percentage, sodium adsorption ratio, magnesium hazard index, and residual sodium carbonate. The results indicated that groundwater was generally suitable with respect to sodium adsorption ratio and residual sodium carbonate, while most samples were also acceptable according to soluble sodium percentage, Kelly index, and sodium percentage. However, magnesium hazard index exceeded the permissible limit in the majority of samples, indicating magnesium-related risk to soil quality. Overall, the groundwater of Umerkot District is largely unsuitable for drinking and shows mixed suitability for irrigation, with magnesium hazard emerging as the main agricultural concern.

Keywords: Physicochemical characteristics, groundwater, suitability for irrigation, arid, semi-arid regions.

Introduction

Groundwater is a vital source of drinking and irrigation water in arid and semi-arid regions worldwide, particularly in areas, where surface water resources are limited or unreliable (Khan and Jhariya, 2017). However, rapid population growth, agricultural intensification, excessive groundwater abstraction, and natural geochemical processes have significantly affected groundwater quality in many regions (Din *et al*., 2023; Dars *et al*., 2022). In developing countries such as Pakistan, groundwater contamination poses serious environmental and public health concerns because rural communities largely depend on untreated groundwater for domestic consumption and agricultural activities. Deterioration in groundwater quality may lead to health risks, soil degradation, and reduced agricultural productivity (Elemile *et al*., 2022; Chaudhary and Satheeshkumar, 2018).

Sindh Province, located in the southeastern part of Pakistan, frequently experiences water scarcity due to limited rainfall, uneven canal water distribution, salinity intrusion, and increasing dependence on groundwater resources (Memon *et al*., 2011; Qureshi, 2018). Umerkot District, situated in the arid region of southeastern Sindh, relies heavily on groundwater extracted for both drinking and irrigation purposes. Previous investigations conducted in parts of Sindh and Umerkot reported elevated salinity, hardness, and the occurrence of certain toxic elements such as arsenic and fluoride in groundwater sources (Kumar *et al*., 2020; Lanjwani *et al*., 2020). Jamali *et al*. (2023) reported elevated concentrations of arsenic and fluoride in groundwater samples from Umerkot city, while Bhatti *et al*. (2018) and Ahmed *et al*. (2020) evaluated groundwater quality in other regions of Sindh using Water Quality Index approaches. However, most previous studies were limited to localized areas or focused only on either drinking-water quality or irrigation suitability, without providing a comprehensive district-wise assessment integrating both aspects.

Groundwater quality assessment using the Water Quality Index (WQI) and irrigation suitability indices has become a widely accepted approach for evaluating overall water usability. WQI simplifies complex hydrochemical data into a single value representing drinking-water suitability (Sarkar *et*

Corresponding author e-mail: saira.mustafa13te64@gmail.com

al., 2021), whereas indices such as Sodium Adsorption Ratio (SAR), Soluble Sodium Percentage (SSP), Kelly Index (KI), Magnesium Hazard Index (MHI), Residual Sodium Carbonate (RSC), and Sodium Percentage are commonly used to evaluate irrigation suitability and potential impacts on soil properties and crop growth (Adimalla *et al*., 2020; Kumar *et al*., 2016; Elemile *et al*., 2022). The integrated assessment of drinking and irrigation suitability provides a more comprehensive understanding of groundwater usability in arid environments.

Despite the importance of groundwater in Umerkot District, no previous study has comprehensively evaluated groundwater suitability for both drinking and irrigation purposes using an integrated hydrochemical and index-based approach at the district scale. Therefore, the present study aims to: (i) assess the physicochemical characteristics of groundwater in Umerkot District, (ii) evaluate groundwater suitability for drinking using the Water Quality Index (WQI), (iii) determine irrigation suitability using multiple irrigation water quality indices, and (iv) identify the dominant hydrochemical characteristics and spatial distribution patterns of groundwater quality across the study area. The findings of this study will contribute to better groundwater management and support sustainable water-resource planning in arid regions of Sindh, Pakistan.

Materials and Methods

Study Area

Umerkot District is located in the southeastern part of Sindh Province, Pakistan, between latitudes 24°54′–25°47′ N and longitudes 69°11′–70°18′ E (Fig. 1). The district covers an area of approximately 3,209 km² and is administratively divided into four tehsils: Umerkot, Kunri, Samaro, and Pithoro (Jamali *et al*., 2023; Maitlo *et al*., 2024).

Hydrogeological Setting

The study area is located within the tail reach of the Nara Canal command area in Umerkot District, Sindh. The district is served by two major perennial canals: the Nara Canal and the Mithrao Canal. The region is arid, receiving less than 40 mm of annual rainfall, and surface water is supplied through a rotational system that allocates weekly turns to distributaries and minors. The Eastern Nara Canal marks the boundary between the irrigated tract and the desert region. Groundwater occurrence and recharge in the area are influenced by local sub-canals, including Kotwah, Chorwah, Tharwah, and Khejrariwah. The local population mainly relies on groundwater extracted through hand pumps for domestic use (PESA, District Umerkot, 2014).

Geological Setting

The study area is located north of the Nagar Parker Igneous Complex and is characterized by recent fluvial deposits and older aeolian sediments. The fluvial deposits include lower terrace floodplain sediments and streambed deposits of extinct drainage systems. In contrast, the aeolian deposits are dominated by longitudinal sand dunes interspersed with playa-like depressions. These depositional features indicate the interaction of past fluvial activity and ongoing aeolian processes in shaping the geology of the area (Fig. 2).

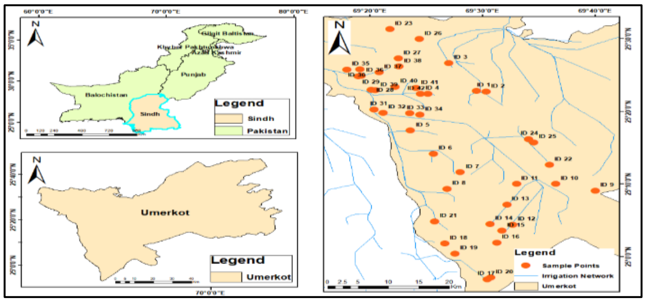

Fig. 1. Location map of the study area.

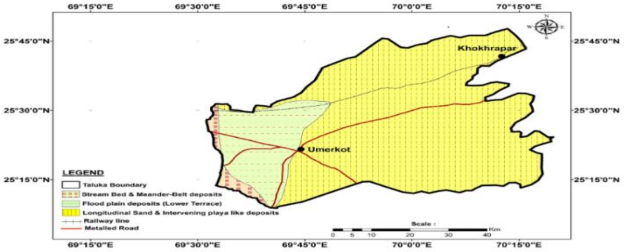

Fig. 2. Geological map of the study area
(modified from Geological Map of Sindh, 2012).

Sample Collection and Preservation

Groundwater sampling was conducted following a preliminary reconnaissance survey of the study area. To ensure representative spatial coverage, an 8 × 8 km grid was superimposed across the district, and groundwater sampling locations were selected accordingly (Fig. 3). A total of 42 groundwater samples were collected from hand pumps distributed throughout the district for the assessment of drinking and irrigation suitability.

Samples were collected in 250 ml polyethylene bottles and filtered through a 0.45 µm membrane filter. Each bottle was properly labeled with sample ID and geographic coordinates recorded using a Garmin GPS device, while additional field observations including water level, depth, and temperature were also noted. Electrical conductivity (EC), total dissolved solids (TDS), and pH were measured in situ using a portable Hanna pH/EC/TDS meter. After collection, all samples were preserved and transported in ice-filled containers at approximately 4 °C to the Advanced Water and Wastewater Quality Control Laboratory, U.S.-Pakistan Center for Advanced Studies in Water, Mehran University of

Engineering and Technology, Jamshoro, for detailed laboratory analysis.

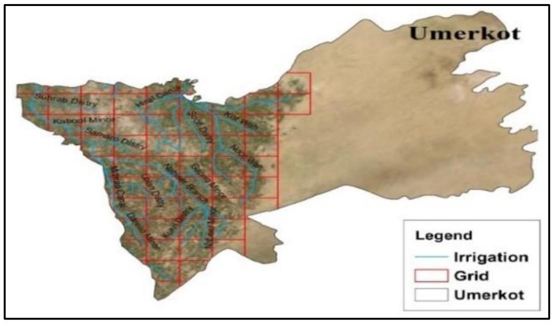

Fig. 3. 8 × 8 km grid overlay of Umerkot District.

Quality Assurance and Quality Control (QA/QC)

Quality assurance and quality control procedures were implemented throughout sampling and laboratory analysis to ensure data reliability and analytical accuracy. Approximately 10% of the total samples were collected and analyzed as duplicate samples to evaluate analytical precision. Calibration of field instruments was performed daily using standard calibration solutions before field measurements. Laboratory analyses were carried out according to APHA (2017) standard methods using properly calibrated instruments and analytical-grade reagents.

Blank samples and standard reference solutions were periodically analyzed to minimize analytical errors and verify instrument performance. The ionic balance error for major cations and anions was maintained within an acceptable limit of ±5%, indicating good analytical accuracy. Detection limits and recovery efficiencies for measured parameters were maintained within acceptable laboratory standards.

Physicochemical Analysis

The collected groundwater samples were analyzed for major physicochemical parameters including pH, EC, TDS, total hardness (TH), bicarbonate (HCO_3^-), chloride (Cl^-), sulfate (SO_4^{2-}), fluoride (F^-), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), and arsenic (As). Analytical procedures followed the standard methods recommended by APHA (2017). The analyzed parameters and their comparison with WHO drinking-water guidelines were used to evaluate groundwater suitability for domestic and irrigation purposes.

Hydrochemical Analysis

Correlation analysis was first performed to identify relationships among physicochemical parameters and major ions in groundwater samples. The analysis helped determine possible common sources, controlling factors, and hydrochemical processes affecting groundwater quality. Statistical significance levels of $p < 0.05$ and $p < 0.01$ were considered during interpretation of the correlation matrix. To further interpret groundwater chemistry and identify dominant geochemical processes, Piper trilinear diagrams and Gibbs diagrams were used. The Piper diagram was applied to classify groundwater into different hydrochemical facies based on the relative concentrations of major cations and anions (Piper, 1953). The Gibbs diagram was used to determine the relative influence of evaporation, rock–water interaction, and precipitation on groundwater chemistry (Gibbs, 1970).

Groundwater Quality Index (WQI)

Groundwater suitability for drinking purposes was evaluated using the Water Quality Index (WQI), which integrates multiple physicochemical parameters into a single numerical value representing overall water quality (Sarkar *et al*., 2021). Eight parameters, namely pH, TDS, Ca^{2+}, Mg^{2+}, Na^+, Cl^-, K^+, and HCO_3^-, were selected for WQI calculation based on their significance to drinking-water quality and public health. Each parameter was assigned a weight (w_i) ranging from 1 to 5 according to its relative importance. The relative weight, W_i, was calculated using:

$$W_i = \frac{w_i}{\sum wi}$$

Where W_i is the relative weight, w_i is the assigned weight of each parameter, and Σw_i is the sum of all assigned weights. The assigned weights and corresponding WHO guidelines are shown in Table 1.

Table 1. Assigned weights for WQI model with WHO limit.

Parameters	WHO limit	Assigned weight (wi)	Relative weight (Wi)
pH	6.5–8.5	4	0.148
TDS	≤ 1000 mg/l	4	0.148
Ca^{2+}	≤ 75 mg/l	3	0.112
Mg^{2+}	≤ 50 mg/l	3	0.112
Na^+	≤ 200 mg/l	3	0.112
Cl^-	≤ 250 mg/l	3	0.112
K^+	≤ 12 mg/l	3	0.112
HCO_3^-	≤ 200 mg/l	4	0.148
		Σwi=27	ΣW_i =1.00

The quality rating scale (Q_i) for each parameter was determined using:

$$Q_i = 100 \times \frac{C_i - Vi}{S_i - V_i}$$

Where $C_i$the measured concentration of the paramete, S_i is the WHO standard permissible limit, and V_i represents the ideal value of the parameter (7.0 for pH and 0 for other parameters).

The sub-index (SI_i) was computed as:

$$SI_i = W_i \times Q_i$$

The overall WQI value was obtained by summing all sub-indices:

$$WQI = \sum SI_i$$

The computed WQI values were classified into five categories: excellent (<50), good (50–100), poor (100–200), very poor (200–300), and unsuitable for drinking (>300) (Ahmed *et al*., 2020).

Irrigation Water Quality Indices

Groundwater suitability for irrigation was evaluated using six widely accepted irrigation indices: Sodium Adsorption Ratio (SAR), Soluble Sodium Percentage (SSP), Kelly Index (KI), Sodium Percentage, Magnesium Hazard Index (MHI), and Residual Sodium Carbonate (RSC). These indices are commonly used to evaluate sodium hazard, salinity risk, soil permeability, and magnesium-related impacts on agricultural productivity (Adimalla *et al*., 2020, Kumar *et al*., 2016; Elemile *et al*., 2022). The irrigation indices were calculated using standard hydrochemical equations based on ionic concentrations expressed in milliequivalents per liter (meq/l). The calculated values were compared with standard classification criteria to determine groundwater suitability for irrigation use (Table 2).

Table 2. Classification of irrigation indices.

Indices	Formula	Range	Suitability Classification
SSP	$\frac{\text{Na}}{(\text{Ca}+\text{Mg}+\text{Na})} \times 100$	<50%	Good
		>50%	Not good
KI	$\frac{\text{Na}}{(\text{Mg}+\text{Ca})}$	<1	Suitable
		>1	Unsuitable
%Na	$\frac{(\text{Na}+\text{K})}{(\text{Ca}+\text{Mg}+\text{Na}+\text{K})} \times 100$	<20	Excellent
		20–40	Good
		40–60	Permissible
		60–80	Doubtful
		>80	Unfit
SAR	$\frac{\text{Na}}{\sqrt{\frac{(\text{Ca}+\text{Mg})}{2}}}$	<10	Excellent
		10–18	Good
		18–26	Doubtful
		>26	Unfit
MHI	$\frac{\text{Mg}}{(\text{Mg}+\text{Ca})} \times 100$	<50%	Suitable
		>50%	Unsuitable
RSC	$(\text{CO}_3 + \text{HCO}_3) - (\text{Ca}+\text{Mg})$	<1.25	Good
		1.25–2.50	Doubtful
		>2.50	Unfit

Spatial Distribution Mapping of WQI and Irrigation Indices

Spatial distribution maps of the Water Quality Index (WQI) and irrigation water quality indices were prepared using ArcGIS software to evaluate spatial variation in groundwater suitability across the study area. The Inverse Distance Weighting (IDW) interpolation technique was applied to generate continuous spatial prediction maps from the sampled locations. These maps helped in identifying areas with poor drinking-water quality and zones showing varying irrigation suitability based on indices such as KI, %Na, MHI, SSP, SAR, and RSC.

Results and Discussion

Physicochemical Characteristics of Groundwater

The hydrochemical analysis of 42 groundwater samples revealed considerable spatial variation in groundwater quality across Umerkot District. The descriptive statistics of physicochemical parameters and their comparison with WHO drinking-water standards are presented in Table 3. Several parameters exceeded the permissible limits in a significant proportion of samples, indicating deterioration in groundwater quality and potential risks for drinking and irrigation use. The pH values ranged from 5.22 to 7.20, with a mean value of 6.32 ± 0.45, indicating slightly acidic to near-neutral groundwater conditions. Approximately 50% of the samples fell below the WHO permissible range (6.5–8.5), suggesting acidic groundwater in several locations. Acidic conditions may enhance mineral dissolution and increase the mobility of dissolved ions and trace elements within the aquifer system.

Electrical conductivity (EC) and total dissolved solids (TDS), which reflect groundwater salinity and mineralization, exhibited wide variation throughout the study area. EC values ranged from 518 to 3070 µS/cm, with 69% of samples exceeding the WHO guidelines. Similarly, TDS ranged from 284.9 to 1773 mg/l, with 24% of samples exceeding the permissible limit. Elevated EC and TDS values indicate high ionic concentration and groundwater salinization, likely associated with evaporation processes, prolonged water–rock interaction, and dissolution of soluble minerals under arid climatic conditions. Similar observations have been reported in arid and semi-arid regions of Sindh and other parts of Pakistan (Dars *et al*., 2022; Din *et al*., 2023).

Total hardness (TH) varied between 75 and 1150 mg/l, with a mean value of 490.05 ± 281.33 mg/l, indicating that groundwater in most locations is hard to very hard. High hardness was mainly associated with elevated concentrations of magnesium and calcium. Magnesium concentrations ranged from 0.48 to 633.75 mg/l, and 85% of samples exceeded the WHO permissible limit, whereas calcium exceeded the permissible limits in 33% of samples. The

Table 3. Descriptive statistics of physicochemical parameters and their compliance with WHO guidelines.

Parameter	WHO limit	Min	Max	Mean ± SD	Within WHO limit (%)	Exceed WHO limit (%)
pH	6.5–8.5	5.22	7.20	6.32 ± 0.45	50	50
EC (µS/cm)	≤ 1000	518	3070	1370.12 ± 558.42	31	69
TDS (mg/l)	≤ 1000	284.90	1773.00	817.79 ± 383.00	76	24
TH (mg/l)	≤ 300	75	1150	490.05 ± 281.33	50	50
HCO_3^- (mg/l)	≤ 200	0	735	127.26 ± 144.25	83	17
Ca^{2+} (mg/l)	≤ 75	0.93	305.43	100.57 ± 76.53	67	33
Mg^{2+} (mg/l)	≤ 50	0.48	633.75	222.41 ± 166.96	15	85
Na^+ (mg/l)	≤ 200	0	876	355.55 ± 222.33	28	72
K^+ (mg/l)	≤ 12	0.30	76.11	31.02 ± 19.33	50	50
As (mg/l)	≤ 0.05	0	0.17	0.02 ± 0.04	79	21
Cl^- (mg/l)	≤ 250	30	592	179.00 ± 128.79	86	14
SO_4^{2-} (mg/l)	≤ 250	27.45	111.66	62.03 ± 24.19	100	0
F^- (mg/l)	≤ 1.5	0.07	2.60	0.65 ± 0.62	90	10

dominance of magnesium over calcium suggests intensive dissolution of magnesium-bearing minerals and possible geogenic control on groundwater chemistry. Excessive hardness may reduce water palatability and create scaling problems in domestic water systems.

Sodium was identified as the dominant cation in groundwater, ranging from 0 to 876 mg/l, with 72% of samples exceeding the WHO limit. Elevated sodium concentrations indicate salinity enrichment and may result from ion-exchange reactions and dissolution of evaporitic minerals. Potassium concentrations also exceeded the permissible limit in nearly half of the samples. Among the major anions, chloride was the dominant anion, while sulfate concentrations remained within WHO permissible limit in all samples. The predominance of sodium and chloride indicates salinization processes and mineral weathering as major contributors to groundwater chemistry.

Fluoride concentrations remained within permissible limit in most groundwater samples; however, localized fluoride enrichment was observed in a few locations. Arsenic concentrations exceeded WHO limits in 21% of samples, which is of particular concern because long-term consumption of arsenic-contaminated groundwater may pose severe health risks. Arsenic contamination has also been previously reported in groundwater systems of Sindh Province (Jamali *et al*., 2023). Overall, the dominant ionic order observed in groundwater was:

Cations:
$Na^+ > Mg^{2+} > Ca^{2+} > K^+$

Anions:
$Cl^- > HCO_3^- > SO_4^{2-} > F^-$

The dominance of Na^+ and Cl^- suggests that groundwater chemistry is primarily controlled by salinity enrichment, evaporative concentration, and dissolution of halite and other evaporitic minerals.

Correlation Analysis of Hydrochemical Parameters

The correlation matrix (Fig. 4) revealed several statistically significant relationships among groundwater quality parameters, indicating common hydrochemical sources and processes. A strong positive correlation was observed between EC and TDS, demonstrating that groundwater salinity is primarily controlled by dissolved ionic constituents. Sodium also exhibited strong positive correlation with EC and chloride, indicating that salinity is largely associated with sodium chloride enrichment and mineral dissolution processes. Magnesium showed positive correlation with total hardness, confirming that magnesium is a major contributor to groundwater hardness in the study area. Similarly, calcium also showed moderate correlation with hardness, although its contribution was lower compared to magnesium. The positive association among Na^+, Cl^-, and EC suggests evaporative concentration and geochemical weathering under may influence arsenic mobilization in groundwater. Overall, the correlation analysis suggests that groundwater chemistry arid climatic conditions. Arsenic showed weak to moderate correlation with several major ions, indicating that both geogenic processes and localized hydrochemical conditions is mainly governed by mineral dissolution, ion-exchange reactions, salinization, and evaporation processes.

	EC	pH	TDS	TH	HCO3	F	SO4	Cl	Mg	Ca	K	Na	As
EC	1.00	-0.07	0.85	0.54	0.19	0.08	0.06	0.27	0.25	0.45	0.03	0.12	0.10
pH	-0.07	1.00	0.11	-0.14	-0.58	-0.21	-0.06	0.12	0.11	-0.02	0.39	0.34	0.39
TDS	0.85	0.11	1.00	0.62	0.01	0.15	0.24	0.30	0.48	0.50	0.33	0.42	0.35
TH	0.54	-0.14	0.62	1.00	0.18	0.16	0.28	0.31	0.33	0.51	0.14	0.19	0.23
HCO3	0.19	-0.58	0.01	0.18	1.00	0.37	0.04	-0.08	0.03	0.17	-0.23	-0.17	-0.33
F	0.08	-0.21	0.15	0.16	0.37	1.00	0.65	0.16	0.41	0.29	0.42	0.04	0.01
SO4	0.06	-0.06	0.24	0.28	0.04	0.65	1.00	0.27	0.45	0.20	0.42	0.20	0.24
Cl	0.27	0.12	0.30	0.31	-0.08	0.16	0.27	1.00	0.68	0.58	0.57	0.40	0.66
Mg	0.25	0.11	0.48	0.33	0.03	0.41	0.45	0.68	1.00	0.74	0.69	0.48	0.63
Ca	0.45	-0.02	0.50	0.51	0.17	0.29	0.20	0.58	0.74	1.00	0.37	0.24	0.40
K	0.03	0.39	0.33	0.14	-0.23	0.42	0.42	0.57	0.69	0.37	1.00	0.68	0.62
Na	0.12	0.34	0.42	0.19	-0.17	0.04	0.20	0.40	0.48	0.24	0.68	1.00	0.61
As	0.10	0.39	0.35	0.23	-0.33	0.01	0.24	0.66	0.63	0.40	0.62	0.61	1.00

Fig. 4. Correlation matrix of physicochemical parameters (pH, EC, TDS, TH), anions (HCO_3^-, Cl^-, SO_4^{2-}, F^-), cations (Ca^{2+}, Mg^{2+}, Na^+, K^+), and arsenic (As) in groundwater samples.

Hydrochemical Facies and Geochemical Processes

The Piper trilinear diagram (Fig. 5) was used to identify groundwater hydrochemical facies and dominant geochemical processes. Most groundwater samples were concentrated within the Ca–Mg–Cl–SO_4 and mixed Ca–Na–HCO_3 facies fields, indicating dominance of alkaline earth metals and strong acidic anions. The hydrochemical facies suggest that groundwater chemistry is primarily controlled by rock–water interaction, dissolution of evaporitic minerals such as gypsum and halite, and salinization processes. The dominance of chloride and sulfate over bicarbonate in several samples reflects advanced hydrochemical evolution and evaporative concentration under arid environmental conditions. The elevated Na^+ concentrations also indicate possible ion-exchange reactions, where calcium and magnesium in groundwater are replaced by sodium adsorbed on aquifer materials. Similar hydrochemical facies have been reported in groundwater systems of arid and semi-arid regions of Pakistan and India (Kumar *et al*., 2016; Adimalla *et al*., 2020).

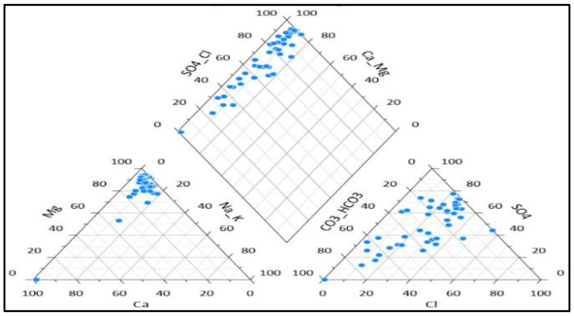

Fig. 5. Piper plot showing the hydrochemical facies of groundwater in the study area.

The Gibbs diagram (Fig. 6) was also used to assess the dominant geochemical processes influencing groundwater in the study area. The majority of samples plotted in the evaporation-dominated field, confirming that salinization due to evaporation is the primary process affecting groundwater chemistry in Umerkot District. This finding is consistent with the high concentrations of sodium, chloride, and total dissolved solids observed in the groundwater.

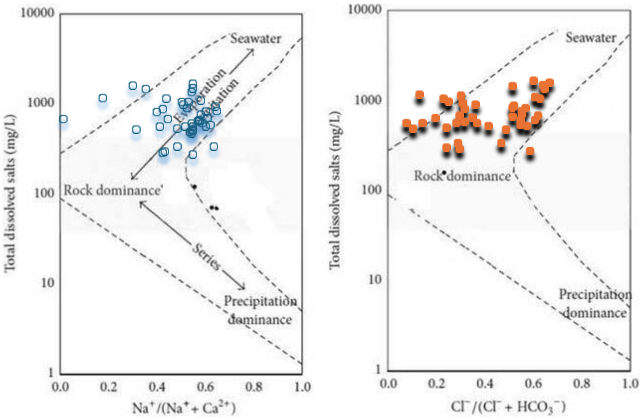

Fig. 6. Gibbs diagram showing the dominant geochemical processes controlling groundwater chemistry.

Groundwater Quality Assessment for Drinking Purposes

The Water Quality Index (WQI) was used to evaluate overall groundwater suitability for drinking purposes. The calculated WQI values ranged from good to unfit categories, reflecting substantial deterioration in groundwater quality throughout the study area. Among the 42 groundwater samples, only 7% were classified as good quality, whereas 33% were categorized as poor, 38% as very poor, and 21% as unsuitable for drinking. No sample fell within the excellent category. The predominance of poor and very poor WQI classes indicates widespread groundwater quality degradation in Umerkot District (Table 4). The elevated WQI values were mainly influenced by high EC, magnesium, sodium, total hardness, and chloride concentrations. These parameters contributed significantly to groundwater mineralization and salinity, thereby reducing drinking-water suitability. Similar deterioration in groundwater quality has been reported in other arid regions where evaporation and groundwater overexploitation enhance dissolved salt concentrations (Elemile *et al*., 2022; Din *et al*., 2023).

Spatial distribution mapping of WQI (Fig. 7) revealed that poor to very poor groundwater quality dominates most parts of the district. Areas classified as unsuitable for drinking were concentrated in localized clusters, suggesting spatial heterogeneity in groundwater contamination and hydrochemical evolution. In contrast, only a few isolated pockets exhibited comparatively better groundwater quality. The spatial variation of WQI may be associated with differences in lithology, groundwater residence time, evaporation intensity, and local recharge conditions. The results indicate that untreated groundwater from many parts of the district may not be safe for direct human consumption.

Table 4. Water Quality Index (WQI) of groundwater samples.

Sample	Latitude	Longitude	WQI	Category of Groundwater
1	25.38º	69.49179º	209.13	very poor
2	25.37815º	69.50569º	174.51	poor
3	25.44401º	69.45071º	230.74	very poor
4	25.37345º	69.40888º	252.30	very poor
5	25.28941º	69.39411º	248.35	very poor
6	25.23618º	69.42829º	132.61	poor
7	25.19383º	69.46796º	374.58	unfit
8	25.15542º	69.44814º	170.78	poor
9	25.1514º	69.66748º	247.71	very poor
10	25.16686º	69.60886º	93.67	good
11	25.16699º	69.55125º	171.10	poor
12	25.07361º	69.54518º	303.56	unfit
13	25.11942º	69.5367º	261.84	very poor
14	25.07516º	69.5117º	421.75	unfit
15	25.05942º	69.52979º	131.22	poor
16	25.0325º	69.52166º	146.01	poor
17	24.94851º	69.50793º	194.87	poor
18	25.03009º	69.44468º	296.32	very poor
19	25.00733º	69.46042º	242.51	very poor
20	24.95214º	69.51281º	219.13	very poor
21	25.08085º	69.42968º	264.43	very poor
22	25.21058º	69.59989º	98.20	good
23	25.52138º	69.36405º	146.26	poor
24	25.26966º	69.56933º	225.25	very poor
25	25.26184º	69.57632º	280.09	very poor
26	25.49878º	69.40727º	141.61	poor
27	25.45442º	69.37601º	141.16	poor
28	25.38237º	69.33567º	163.53	poor
29	25.41379º	69.31687º	160.56	poor
30	25.42942º	69.31916º	376.13	unfit
31	25.33719º	69.33988º	323.43	unfit
32	25.32972º	69.35386º	220.73	very poor
33	25.3286º	69.39322º	191.13	poor
34	25.32517º	69.40812º	282.81	very poor
35	25.42872º	69.3003º	190.05	poor
36	25.4144º	69.32066º	451.49	unfit
37	25.42241º	69.34744º	254.20	very poor
38	25.43595º	69.37691º	352.83	unfit
39	25.38149º	69.34153º	99.89	good
40	25.38925º	69.37155º	454.18	unfit
41	25.38626º	69.40223º	432.66	unfit
42	25.37295 º	69.41952 º	255.24	very poor

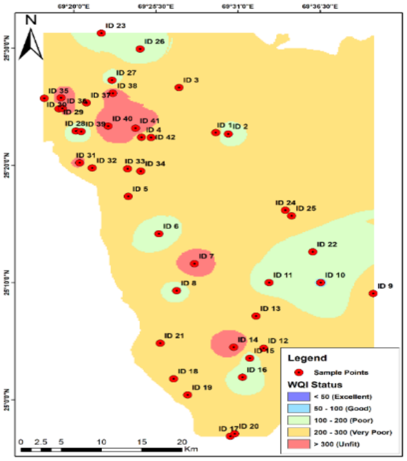

Fig. 7. Spatial variation of groundwater quality based on the Water Quality Index (WQI) in the study area.

Groundwater Suitability for Irrigation

Groundwater suitability for irrigation was evaluated using SSP, KI, %Na, SAR, MHI, and RSC indices. The results demonstrated mixed irrigation suitability across the study area (Table 5).

Table 5. Suitability of groundwater quality for irrigation activities based on six indices.

Sample	SSP	KI	%Na	SAR	MHI	RSC
1	41.91	0.75	43.9	4.43	73.69	-13.48
2	49.03	0.99	50.67	4.89	74.13	-8.68
3	50.51	1.05	52.03	6.31	77.98	-14.87
4	44.27	0.81	45.49	4.41	71.02	-11.46
5	34.44	0.53	35.32	3.71	90.29	-17.77
6	59.84	1.68	64.35	5.12	57.02	-3.83
7	6.16	0.07	6.95	0.75	76.67	-57.12
8	32.02	0.49	34.05	2.15	64.63	-4.84
9	55.06	1.39	60.31	6.02	94.18	-6.12
10	33.79	0.53	36.27	2.37	64.61	-8.83
11	52.45	1.13	53.54	4.91	86.13	-5.36
12	39.24	0.66	40.09	4.51	59.5	-20.86
13	30.31	0.45	33.1	3.49	64.26	-26.62
14	21.64	0.28	22.8	2.75	70.82	-45.79
15	56.5	1.37	58.73	4.82	64.37	-5.37
16	0	0	8.18	0	45.85	2.62
17	31.89	0.49	34.63	3.68	86.77	-27.04
18	18.48	0.23	21.11	2.53	89.3	-56.28
19	32.5	0.49	33.9	3.52	83.6	-23.92
20	37.73	0.63	40.21	3.51	57.37	-14.66
21	16.49	0.2	18.18	2.12	72.35	-54

Sample	SSP	KI	%Na	SAR	MHI	RSC
22	29.1	0.44	33.55	2.13	71.61	-10.59
23	44.98	0.86	47.48	5.09	78.81	-17.09
24	63.32	1.79	64.69	8.88	93.8	-11.68
25	22.09	0.3	25.32	1	56.62	-5.77
26	47.58	0.96	50.43	5.41	94.59	-14.25
27	52.42	1.18	55.54	3.77	65.72	-1.25
28	51.18	1.13	54.56	5.15	79.63	-10.11
29	42.56	0.79	46.1	4.12	93.16	-12.41
30	47.03	0.92	48.69	7.05	71.38	-17.51
31	33.8	0.52	35.34	4.56	79.86	-37.6
32	53.03	1.18	55.14	7.86	81.23	-21.88
33	28	0.4	29.5	2.67	76.62	-22.37
34	56.16	1.32	57.48	9.18	83.87	-23.47
35	42.79	0.77	44.35	5.17	79.83	-22.25
36	39.34	0.67	40.99	7.13	82.44	-56.88
37	58.83	1.51	61.11	9.61	83.17	-19.43
38	53.42	1.22	56.36	9.3	78.42	-28.39
39	34.37	0.54	36.35	2.71	76.19	-12.28
40	34.66	0.55	36.71	5.85	85.72	-56.75
41	40.13	0.7	42.33	6.9	81.86	-49.08
42	59.11	1.51	60.83	9.04	74.36	-17.13

Kelly Index (KI)

According to the Kelly Index (Fig. 8), 29 samples (69%) had KI values <1 and were therefore suitable for irrigation, while 13 samples (31%) had KI values >1 and were classified as unsuitable. These results suggest that the majority of groundwater samples are acceptable based on KI, but nearly one-third may contribute to excess sodium in irrigated soils.

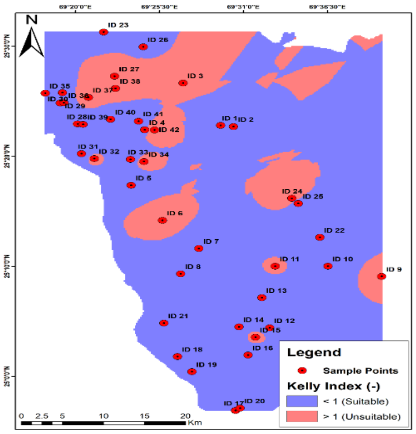

Fig. 8. Spatial distribution map of Kelly Index.

Sodium Percentage

The sodium percentage (Fig. 9) results showed variable irrigation suitability. Among 42 samples, 3 samples (7%) fell in the excellent category, 14 (33%) in good category, 20 (48%) in the permissible category, and 5 samples (12%) in the doubtful category. No sample was classified as unfit on the basis of Na percentage. Overall, these results suggest that most groundwater samples are suitable to moderately suitable for irrigation, although some may require careful management.

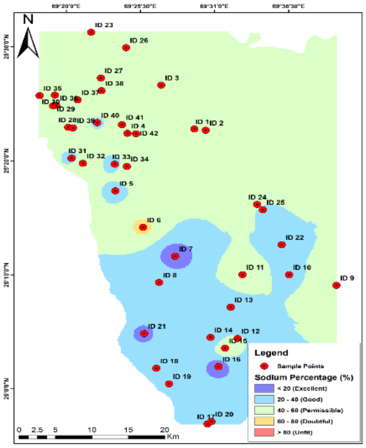

Fig. 9 Spatial distribution map of sodium percentage.

Magnesium Hazard Index (MHI)

In contrast, the Magnesium Hazard Index indicated serious limitations for irrigation suitability (Fig. 10). Only 1 sample (2%) had the MHI value below 50% and was considered suitable, whereas 41 samples (98%) exceeded the permissible limit. The predominance of high MHI values indicates a strong magnesium hazard, which may negatively affect soil quality and crop performance over time.

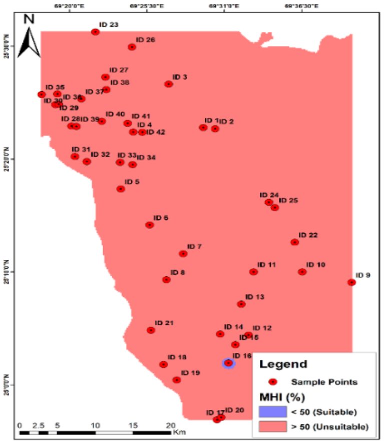

Fig. 10. Spatial distribution map of Magnesium Hazard Index.

Soluble Sodium Percentage (SSP)

Based on SSP values (Fig. 11), 29 samples (69%) were within the suitable range (<50%), whereas 13 samples (31%)

exceeded the acceptable limit (>50%). This indicates that most samples are suitable with respect to soluble sodium percentage, although a considerable proportion may pose sodium-related problems under prolonged irrigation use.

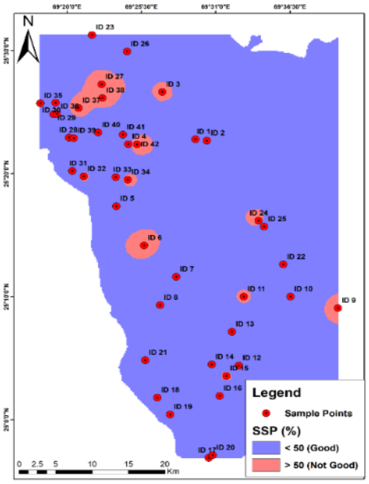

Fig. 11. Spatial distribution map of soluble sodium percentage.

Sodium Adsorption Ratio (SAR)

The SAR values (Fig. 12) revealed a more favorable situation. All 42 samples (100%) had SAR values below 10, placing them in the excellent category for irrigation. This suggests that, in terms of sodium adsorption hazard, the groundwater is suitable for irrigation, and is less likely to adversely affect soil infiltration and structure.

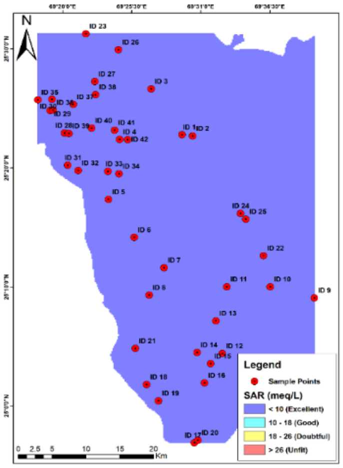

Fig. 12. Spatial distribution map of sodium adsorption ratio.

Residual Sodium Carbonate (RSC)

The RSC results (Fig. 13) showed that 41 samples (98%) were in the good category (<1.25), while only 1 sample (2%) was unfit (>2.50). No sample fell in the doubtful category. This suggests that residual sodium carbonate is not a major irrigation concern in most parts of the study area.

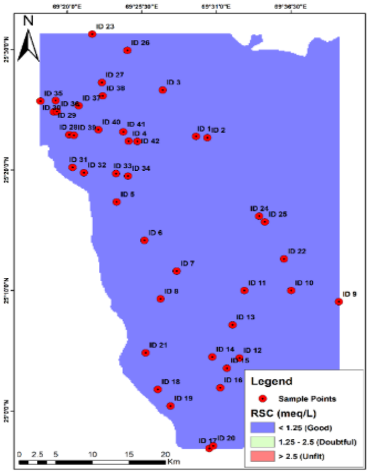

Fig. 13. Spatial distribution map of residual sodium carbonate.

Overall, the irrigation assessment indicates mixed groundwater suitability in Umerkot District. The groundwater is generally suitable with respect to SAR and RSC, and a majority of samples are also acceptable according to SSP, KI, and %Na. However, the very high MHI values in most samples point to magnesium-related hazards as the principal constraint for irrigation use. Therefore, although groundwater can be used for irrigation in many parts of the study area, continuous use without proper soil and water management may lead to deterioration in soil condition and reduced agricultural productivity.

Comparison with Previous Studies

The findings of the present study indicate poorer groundwater quality in Umerkot District than that reported in some previous studies conducted in Pakistan and elsewhere. Ahmed *et al*. (2020) assessed drinking water quality in primary schools across 13 districts of Sindh, including Umerkot, and reported that 74% of samples were classified as good or excellent, whereas only 26% fell into the poor, very poor, or unfit categories. In contrast, the present study showed that only 7% of groundwater samples were of good quality, while 33% were poor, 38% very poor, and 21% unfit for drinking. This difference may be attributed to variation in sampling sources, as the previous study focused on school drinking water supplies (Fig. 14), which may include treated or managed sources, whereas the present study analyzed untreated groundwater collected directly from hand pumps.

For irrigation suitability, the present results are partly consistent with previous studies in showing that some irrigation indices support groundwater use, but they also reveal important local limitations. Similar to earlier studies, sodium adsorption ratio and residual sodium carbonate indicated generally suitable conditions for irrigation. However, unlike studies such as Elemile *et al*. (2022), which reported overall better irrigation water quality with low magnesium hazard, the present study found that magnesium hazard index exceeded the permissible limit in most samples. This suggests that although groundwater in Umerkot may be used for irrigation in many locations, its long-term use could contribute to soil quality deterioration due to magnesium-related hazards. These differences highlight the spatial variability of groundwater quality and emphasize the importance of site-specific assessment before recommending groundwater for drinking or irrigation use.

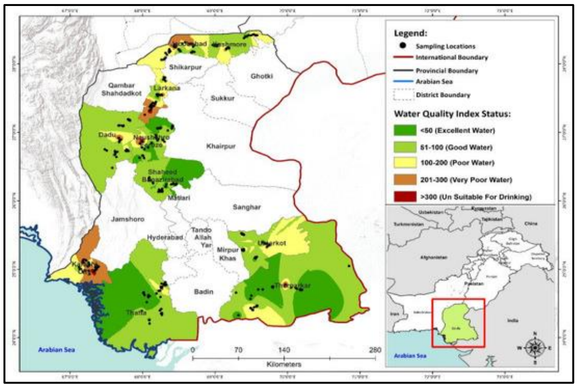

Fig. 14. Spatial distribution of the water quality index of primary schools in Sindh.

Conclusion

The physicochemical conditions of groundwater in Umerkot District showed that several parameters, including electrical conductivity, magnesium, and sodium, exceeded the permissible limits in a considerable number of samples, while total dissolved solids, fluoride, sulfate, chloride, bicarbonate, calcium, and arsenic remained within permissible limits in most cases. Based on WQI classification, none of the groundwater samples fell in the excellent category; only 7% were classified as good, whereas 33% were poor, 38% very poor, and 21% unfit for drinking. These findings indicate that groundwater in most parts of the study area is unsuitable for direct human consumption without treatment. On the other hand, the physicochemical characteristics show that the studied groundwater is generally suitable for irrigation with respect to sodium adsorption ratio and residual sodium carbonate, while most samples were also acceptable according to soluble sodium percentage, Kelly index, and sodium percentage. However, the magnesium hazard index exceeded the permissible limit in the vast majority of samples, indicating that magnesium-related soil deterioration may become a serious constraint under long-term irrigation use. Overall, groundwater in Umerkot District shows limited suitability for drinking and mixed suitability for irrigation. Regular monitoring, appropriate water treatment, and improved soil and water management practices are therefore necessary to protect public health and support sustainable agricultural use of groundwater in the area.

Acknowledgement

The authors would like to express their sincere gratitude to the U.S.-Pakistan Center for Advanced Studies in Water (USPCAS-W), Mehran University of Engineering and Technology, Jamshoro, for providing an excellent academic environment, research facilities, and continuous support for this study.

References

Adimalla, N., Dhakate, R., Kasarla, A. and Taloor, A.K. (2020). Appraisal of groundwater quality for drinking and irrigation purposes in Central Telangana, India. *Groundw. Sustain. Dev*., **10**: 100334.

Ahmed, J., Wong, L. P., Chua, Y. P., & Channa, N. (2020). Drinking water quality mapping using water quality index and geospatial analysis in primary schools of Pakistan. *Water*, **12**(12): 3382.

APHA. (2017). Standard methods for the examination of water and wastewater (23rd ed.). American Public Health Association.

Bhatti, N.B., Siyal, A.A. and Qureshi, A.L. (2018). Groundwater quality assessment using water quality index: A case study of Nagarparkar, Sindh, Pakistan. *Sindh Univ. Res. J., Sci. Ser.*, **50**(2): 227-234.

Chaudhary, V. and Satheeshkumar, S. (2018). Assessment of groundwater quality for drinking and irrigation purposes in arid areas of Rajasthan. *Appl. Water Sci.*, **8**(8): 218.

Dars, R., Qureshi, A.L., Jamali, M.A., Memon, H.A., Kori, S.M. and Oad, S. (2022). Subsurface groundwater aquifer mapping and quality characterization in Matiari district, Sindh, Pakistan. *Environ. Monit. Assess.*, 194(12): Article 2–17.

Din, I.U., Muhammad, S. and Rehman, I.U. (2023). Groundwater quality assessment for drinking and irrigation purposes in the Hangu District, Pakistan. *J. Food Compos. Anal.*, **115**: 104919.

Elemile, O.O., Ibitogbe, E.M., Okikiola, B.T. and Ejigboye, P.O. (2022). Groundwater quality using indices for domestic and irrigation purposes in Akure, Nigeria. *Results Eng*., **13**: 100347.

Geological map of Sindh issued by Geological Survey of Pakistan, 2012.

Gibbs, R.J. (1970). Mechanisms controlling world water chemistry. *Science*, **170**(3962): 1088-1090.

Jamali, M.A., Arian, A.Y., Markhand, A.H. and Kumar, D. (2023). The investigation of heavy metal concentration through GIS-based approach from groundwater of Umerkot city, Sindh, Pakistan. *Arab. J. Geosci*., **16**(5): Article 5.

Khan, R., & Jhariya, D. C. (2017). Groundwater quality assessment for drinking purpose in Raipur city, Chhattisgarh using water quality index and geographic information system. *J. Geol. Soc. India*, **90**(1): 69-76.

Kumar, M., Kumar, S., Thirumoorthy, P., Suresh, M. and Ramesh, S. (2016). Assessment of the groundwater quality for irrigation purposes in Rasipuram Taluk, Tamilnadu, India. *AJRSSH*, **6**(6): 547-560.

Kumar, N., Mahessar, A.A., Memon, S.A., Ansari, K. and Qureshi, A.L. (2020). Impact assessment of groundwater quality using WQI and geospatial tools: A case study of Islamkot, Tharparkar, Pakistan. *Eng. Technol. Appl. Sci. Res.*, **10**(1): 5288-5294.

Lanjwani, M.F., Khuhawar, M.Y. and Khuhawar, T.M.J. (2020). Groundwater quality assessment of Shahdadkot, Qubo Saeed Khan and Sijawal Junejo Talukas of District Qambar Shahdadkot, Sindh. *Appl. Water Sci*., **10**(1): Article 1-18.

Maitlo, S.S., Qureshi, A.L. and Jamali, M.A. (2024). P13-Shallow subsurface aquifer mapping, groundwater and quality characterization in tehsil Samaro District Umerkot. Climate Change and Water Resources (CCWR) Bridging the Gap for SDG6, 120.

Mallano, A. R., Kori, S. M., & Qureshi, A. L. (2022). Assessment of suitability of groundwater quality for drinking and irrigation purposes, and its impact on soil fertility of Muhammad Khan Distributary command area. *In*: International Conference on Environment Sustainability.

Memon, M., Soomro, M., Akhtar, M., & Memon, K. (2011). Drinking water quality assessment in southern Sindh (Pakistan). *EMA*, 177(1-4): 39-50.

Pakistan Emergency Situational Analysis report, District Umerkot, 2014.

Piper, A. M. (1953). A graphic representation in the geochemical interpretation of groundwater analyses. *Eos Trans. AGU*, **25**: 914-923.

Qureshi, A.S. (2018). Challenges and opportunities of groundwater management in Pakistan. Groundwater of South Asia, pp.735-757.

Sarkar, S., Roy, A., Bhattacharjee, S., Shit, P. K., & Bera, B. (2021). Effects of COVID-19 lockdown and unlock on health of Bhutan-India-Bangladesh trans-boundary rivers. *J. Hazard. Mater. Adv*., 4: 100030.

World Health Organization (2017). Guidelines for drinking-water quality. World Health Organization.