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GROUNDWATER QUALITY ASSESSMENT FOR IRRIGATION PURPOSE USING THE IRRIGATION WATER QUALITY INDEX (IWQI) IN MIRPUR KHAS DISTRICT, SINDH, PAKISTAN

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ABSTRACT

This study investigates groundwater quality for irrigation purposes in the Mirpur Khas district of Sindh, Pakistan, employing the Irrigation Water Quality Index (IWQI) as a principal assessment tool. Groundwater samples were collected from thirty bore wells across ten villages during the months of October and November 2018 and analyzed for their physical and chemical parameters using standard laboratory methods. From the analyzed data, critical parameters such as sodium adsorption ratio (SAR), residual sodium carbonate (RSC), sodium percentage (Na%), magnesium adsorption ratio (MAR), and permeability index (PI) were calculated for each water sample to evaluate their suitability for irrigation. The trend of determined major ions was $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ and $HCO_3^- > Cl^- > SO_4^{2-}$. The findings indicated elevated salinity levels in most of the water samples, with electrical conductivity (EC) values ranging from 410 to 6270 μS/cm. The IWQI was computed using parameters EC, SAR, Na+, Cl−, and HCO_3^- to derive a single value that ranks the groundwater quality at each bore well for agricultural applications. The results of the IWQI demonstrated that the groundwater quality spans between low restriction to severe restriction categories, where majority of samples (80%) fell within moderate to high restriction classifications. Consequently, utilizing such water sources for irrigation in the study area, will likely cause soil salinity issues characterized by heavy textures.

Keywords: Groundwater, irrigation, water quality index, Mirpur Khas, Pakistan

INTRODUCTION

Groundwater in Pakistan is subject to ongoing contamination due to multiple factors, including the seepage of sewage, the disposal of industrial effluents onto land, and the excessive application of fertilizers and pesticides (Qureshi, 2020). Furthermore, the proliferation of tubewell installations and the over-extraction of groundwater have resulted in saltwater intrusion into freshwater aquifers. This phenomenon has severely compromised the quality of groundwater resources.

Pakistan ranks as the world's third-largest groundwater consumer for irrigation. About 73% of the land utilized for irrigation in Pakistan relies on groundwater, either directly or indirectly (Qureshi, 2020). Diminishing surface water resources resulting from declining storage capacities and increasing concerns related to climate change pose significant threats to the future of irrigated agriculture, which constitutes approximately 90% of total grain production in Pakistan (Basharat and Tariq, 2015; Zaveri *et al*., 2016). The prevalent arid and semi-arid conditions across much of the country, particularly in Sindh province, necessitate irrigation for sustainable crop production, given the high rates of evapotranspiration coupled with limited and unreliable rainfall. More than 75% of annual precipitation occurs during the monsoon season, from July to September. The contribution of rainfall to agricultural irrigation amounts to approximately 30 billion cubic meters, which covers only 15% of the total crop water requirements (Bhatti and Akhtar, 2002; Khan *et al*., 2016). Consequently, the remaining 85% must be supplemented through irrigation. The scarcity and unpredictability of surface water resources have compelled farmers to extract groundwater to meet irrigation demands, often regardless of the water quality.

The water quality used for irrigation is influenced by the types of salts present and their concentrations. An increase in total salt concentration across various soil types can lead to complications in crop development, ultimately resulting in reduced crop yields. The appropriateness of water for specific agricultural purposes is determined by its long-term effects and the severity of its impacts. The water quality index (WQI), a numerical system utilized for evaluating water quality, was first proposed by Horton in 1965. Meireles *et al*. (2010) conducted a multivariate statistical analysis of water, resulting in developing a novel water quality indicator for irrigation, designated as the irrigation water quality index (IWQI). This index incorporates such parameters as Electrical Conductivity (EC), sodium adsorption ratio (SAR), HCO_3^-, Na^+, and Cl^-. Furthermore, the authors reclassified the WQI for irrigation by considering soil salinity and infiltration rates. This method enables decision-makers to assess the quality of different water types and the associated potential risks based on a comprehensive range of parameters (Sener *et al*., 2021). The IWQI also facilitates the assessment and comparison of diverse water samples, thus preventing detrimental effects on soil and vegetation (Batarseh *et al*., 2021). Moreover, the IWQI forecast makes drilling wells for agricultural use in regions with substantial groundwater salinization more economically feasible (El Bilali and Taleb, 2020). This advanced approach is increasingly being employed in numerous research projects to monitor water quality for irrigation purposes.

Extensive research has been conducted on groundwater quality for drinking purposes in Pakistan (see Daud *et al*., 2017 and Arain *et al*., 2024b for references). However, there has been comparatively less focus on assessing groundwater quality for irrigation purposes (Ali *et al*., 2009; Waheed *et al*., 2010; Lanjwani *et al*., 2020; Baloch *et al*., 2021; Soomro *et al*., 2024). The District Mirpur Khas in Sindh Province, Pakistan, has received little scholarly attention. Only Arain *et al*. (2024b) have examined groundwater quality for drinking, and no data exist on groundwater quality for irrigation use in the area. This research gap highlights a significant lack of knowledge in the current literature, underscoring the importance of the present study. This study primarily aims to assess groundwater suitability in the Mirpur Khas district using the IWQI approach for irrigation purposes.

MATERIALS AND METHODS

Study Area

District Mirpur Khas (Fig. **1**) is located in the southeastern region of Sindh province. According to the 2023 Census, the district has a population of 1.68 million, with approximately 71% living in rural areas and 29% in urban settings. This district is classified as a subtropical desert, characterized by May as the warmest month, with an average temperature of 39.2°C. January is the coldest month, with an average temperature of 20.8°C. The region receives an average annual rainfall of 230 mm, primarily during the monsoon season from July to September. Mirpur Khas is known for its fertile agricultural land, which produces a variety of crops, including mangoes, sugarcane, wheat, bananas, cotton, onions, and chilies. The district has established connections to the Indus River through the Let Wah Canal. Additionally, it is home to several industrial facilities, including sugar and edible oil mills and cotton and fertilizer production plants.

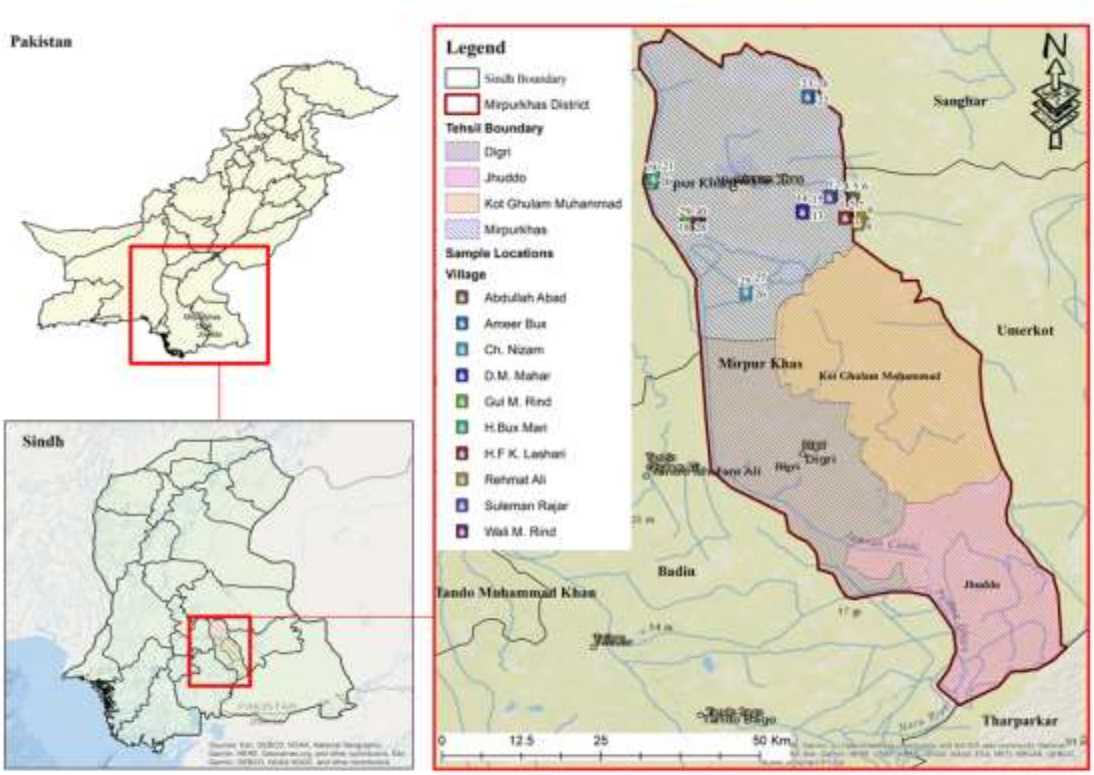

Fig.1. Map illustrating the locations of bore wells in Mirpur Khas district, Sindh province, Pakistan.

Sample Collection

Groundwater samples (n=30) were collected during October and November 2018 from thirty shallow bore wells located across ten villages, with depths ranging from 4.6 to 10.7 m. The sampling locations are illustrated in Fig. **1**, and the corresponding coordinates are listed in Table 1. After removing any standing water, groundwater samples were obtained directly from the hand pumps, using polystyrene bottles pre-soaked in a 10% HNO_3 solution and rinsed with deionized water.

Sample Analyses

EC was measured using a HACH meter (HQ 14d), and the concentration of SO_4^{2-} was determined by a HACH colorimeter (DR-2800). All other parameters were analyzed following the standard procedures outlined in APHA (1998). The analysis of Ca^{2+} was carried out volumetrically using the EDTA (0.01M) titration method. The concentration of Mg^{2+} was calculated using the formula $Mg^{2+} = (TH - 2.5\ Ca^{2+}) \times 0.243$. CO_3^{2-} and HCO_3^- were determined by titration using HCl (0.02 N). The Cl^- concentration was determined using the Argentometric method by titrating with $AgNO_3$ solution (0.014N). The measurements of Na^+ and K^+ were carried out using a digital flame photometer (DV 7101, Italy).

The following indices were calculated using the formulae provided below to evaluate the water quality for irrigation. All concentrations were expressed in meq/L.

Residual sodium carbonate (RSC) (Eaton, 1950)

$$RSC = (CO_3^{2-} + HCO_3^-) - (Ca^{2+} + Mg^{2+})$$

Sodium adsorption ratio (SAR) (Richards, 1954)

$$SAR = Na+ / \sqrt{[(Ca^{2+} + Mg^{2+}) / 2]}$$

Magnesium adsorption ratio (MAR) (Raghunath, 1987)

$$MAR = [(Mg^{2+} / Ca^{2+} + Mg^{2+}) \times 100]$$

Sodium percentage (Na%) (Wilcox, 1955)

$$Na\% = [(Na^+ + K^+) / (Ca^{2+} + Mg^{2+} + Na^+ + K^+)] \times 100$$

Permeability index (PI) (Doneen, 1964)

$$PI = [(Na^+ + \sqrt{HCO_3^-}) / (Ca^{2+} + Na^+ + Mg^{2+})] \times 100$$

To calculate the IWQI, method outlined by Meireles *et al*. (2010) was followed, which is briefly described below. First, the quality measurement (Q_i) value was calculated using the following formula: $Q_i = Q_{imax} - [(X_{ij} - X_{inf})\ Q_{iamp}) / X_{iamp}]$ where Q_{imax} represents the maximum value of Q_i. X_{ij} refers to the observed value of a specific parameter, while X_{inf} indicates the corresponding value at the lower limit of the class to which this parameter belongs Table 2). Q_{iamp} denotes the amplitude of the class, and X_{iamp} refers to the amplitude of the class that includes the parameter. To evaluate X_{iamp} for the first class of each parameter, the upper limit was the highest value observed for that parameter from the water samples analyses.

The IWQI was then calculated using the formula $IWQI = \Sigma\ Q_i \times W_i$, where W_i represents the relative weight of each parameter. The weights for the parameters are as follows: Na^+ = 0.204, Cl^- = 0.194, HCO_3^- = 0.202, SAR = 0.189, and EC = 0.211 (Meireles *et al*., 2010).

RESULTS AND DISCUSSION

Evaluating groundwater quality involves a detailed analysis of the composition of dissolved elements present within the water. This systematic approach ensures a comprehensive understanding of groundwater's characteristics and potential environmental and public health implications. The concentrations of dissolved elements in the groundwater samples, including cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) and anions (HCO_3^-, Cl^-, SO_4^{2-}), and the EC values, are presented in Table 3 and discussed below.

Ionic concentration

Na^+ emerged as the predominant cation, exhibiting concentrations ranging from 36 to 790 mg/L, with a mean value of 221 ± 159 mg/L. This was followed by Ca^{2+} with a mean concentration of 99 ± 64 mg/L and Mg^{2+} with a mean value of 64 ± 37 mg/L (Table 3). K^+ was the least abundant cation, with concentrations ranging from 3.1 to 33.8 mg/L, resulting in an average value of 9.4 ± 7.4 mg/L. Among the anions, HCO_3^- was identified as the dominant anion, with concentrations ranging from 100 to 480 mg/L, yielding a mean value of 326 ± 102 mg/L. This was followed by SO_4^{2-} and Cl^-, which had mean values of 285 ± 197 mg/L and 265 ± 262 mg/L, respectively. Notably, CO_3^{2-} was absent in all analyzed groundwater samples.

According to established guidelines, the acceptable limits for Na^+, Ca^{2+}, Mg^{2+}, and K^+ in irrigation water are 200, 80, 35, and 30 mg/L, respectively (Soomro *et al*., 2024). The results of the present study revealed that 56.7% of samples exceeded the allowable limit for Na^+, 36.7% surpassed the threshold for Ca^{2+}, and 73.3% exceeded the permissible level for Mg^{2+}. In contrast, K^+ concentrations stayed within acceptable limits, with only one sample surpassing the threshold, (Table 3). The permissible limits for HCO_3^-, SO_4^{2-}, Cl^-, and CO_3^{2-} are set at 250, 1000, 250, and 50 mg/L, respectively (Soomro *et al.*, 2024). An analysis of major anions showed that 76.7% of water samples exceeded the limit for HCO_3^-. In contrast, all samples were within the permissible limits for SO_4^{2-} and CO_3^{2-}. However, 36.7% of the samples exceeded the Cl^- permissible limit.

Electrical conductivity (EC)

The EC of groundwater samples varied from 410 to 6270 µS/cm, with a mean value of 2024 ± 1222 µS/cm (Table 3). Only four out of the total samples (n=30) were classified as 'good' (250 to 750 µS/cm) (Table 5). In contrast, thirteen samples were categorized as 'permissible' (750 to 2000 µS/cm), and ten samples were classified as 'doubtful' (2000 to 3000 µS/cm). Additionally, three groundwater samples were determined to be unfit for use, exhibiting EC values exceeding 3000 µS/cm; two of these samples (sample #23 and #24) were collected from Ameer Bux village, while the third sample (sample #16) was sourced from Wali M. Rind village.

Irrigation water typically contains a combination of naturally occurring salts. The quality of the irrigation water, irrigation management practices, and the effectiveness of drainage systems influence the degree to which these salts accumulate in the soil. As the quality of water deteriorates, managing salinity becomes increasingly challenging. Higher salinity levels necessitate more stringent measures to leach salts from the root zone before their concentration reaches levels that may adversely affect crop yield. While water classified as saline or unfit for irrigation can pose risks, it can still be utilized effectively for crop cultivation without causing long-term detrimental effects to plants or soil, provided that enhanced agricultural and management practices are implemented (FAO, 1992). Lime within the soil parent material, coupled with a deep water table and reduced river flow infiltration into the groundwater table, may elevate the soil's electrical conductivity (Stavi *et al*., 2021). Consequently, this condition can render the water unfit for irrigation purposes.

Residual sodium carbonate (RSC)

RSC is utilized to assess the potential adverse effects of CO_3^{2-} and HCO^{3-} on water quality intended for agricultural applications (Singh *et al*., 2020). The quantity of CO_3^{2-} and HCO_3^- over the alkaline earth metal ions, specifically Ca^{2+} and Mg^{2+}, is a significant factor affecting the suitability of groundwater for irrigation purposes. This excess amount of CO_3^{2-} and HCO_3^- is called RSC. The current study's findings indicate that RSC values in the groundwater samples ranged from -19.66 to 1.85 meq/L, with a mean of -4.89 ± 4.7 (Table 4). A negative RSC value suggests a minimal risk of Na^+ accumulation due to sufficient levels of Ca^{2+} and Mg^{2+}. Conversely, a positive value indicates that HCO_3^- and CO_3^{2-} may displace free Ca^{2+} and Mg^{2+} in the soil, consequently allowing Na^+ accumulation. According to Eaton (1950), water is classified based on RSC into three categories: good (< 1.25 meq/L), doubtful (1.25 to 2.50 meq/L), and unsuitable (> 2.50 meq/L). This classification reveals that 96.67 % of the samples fell within the good category, while 3.33 % were doubtful (Table 5). In instances where water exhibits a high concentration of HCO_3^-, there is a tendency for Ca^{2+} and Mg^{2+} to precipitate as CO_3^{2-}, thereby increasing the relative proportion of Na^+ in the water as $NaHCO_3$. Continuous water usage with an RSC exceeding 2.5 meq/L may result in salt accumulation, which can obstruct air and water movement by clogging soil pores and leading to the degradation of the soil's physical condition. The groundwater samples from Mirpur Khas are deemed suitable for irrigation based on the observed values.

Sodium adsorption ratio (SAR)

High concentrations of Na^+ can increase soil alkalinity, which deteriorates soil structure and texture and negatively impacts plant growth (Todd and Mays, 2005; Lanza *et al*., 2019). According to Richards (1954), the SAR for groundwater is categorized into four groups: excellent (SAR < 10), good (SAR 10 to 18), doubtful (SAR 18 to 26), and unsuitable (SAR > 26). The SAR values ranged from 1.32 to 9.83 in the groundwater samples analyzed, with an average of 4.1 ± 2.2 (Table 4). It was noted that all groundwater samples exhibited excellent irrigation quality, as indicated by their SAR values being less than 10 (Table 5). The EC value influences the adverse effects of SAR. A SAR level of 10 in Pakistan is considered a safe threshold (Kinje, 1993). High SAR values above 10 can cause Na^+ to replace Ca^{2+} or Mg^{2+} in soil, damaging its structure. High Na^+ concentration in irrigation water leads to its adsorption by clay particles, displacing Ca^{2+} and Mg^{2+}. This exchange reduces permeability and results in poor drainage, restricting air and water circulation in wet conditions and causing the soil to harden when dry. (Collins and Jenkins, 1996; Saleh *et al*., 1999).

A graphical representation of groundwater data using the US salinity diagram (Richards, 1954) clearly illustrates the salinity hazard, indicated by EC on the x-axis. The SAR represents the alkalinity hazard on the y-axis

(Fig. **2**). The analysis revealed that 33.33% of the samples fell within the high salinity-low sodium class (C3-S1). In comparison, 20% were classified as very high salinity-medium sodium (C4-S2). Additionally, 16.67% of the samples were categorized in the medium salinity-low sodium group (C2-S1), and another 16.67% were placed in the high salinity-medium sodium category (C3-S2). Only one sample was found in the high salinity hazard-low sodium hazard class (C3-S1). Furthermore, one specific sample, designated as number 24 from a well in Ameer Bux village, accounted for 3.33% and was classified under the extremely high salinity-high sodium category (C5-S3).

Groundwater classified within the medium-salinity hazard class (C2) can generally be utilized without special salinity control practices. Water sourced from zones C3–S1 and C3–S2 is regarded as having moderate quality for irrigating semi-tolerant crops. However, samples obtained from high-salinity regions necessitate careful management practices. Water characterized by very high salinity (C4) is typically unfit for irrigation under standard conditions; nevertheless, it may be applied to salt-tolerant plants on permeable soil if managed carefully (Ahmed *et al*., 2013).

Table 1. Villages in the Mirpur Khas district, along with the coordinates of each bore well from which groundwater samples were obtained (HP and MP denote hand pump and motor pump).

Village	S. No.	Coordinate N : E	Depth (m)	Source
Asghar Lashari	1	25°29.32 : 69°10.25	5.5	HP
	2	25°29.33 : 69°10.27	5.5	HP
	3	25°29.36 : 69°10.31	5.5	HP
Abdullah Abad	4	25°30.93 : 69°10.94	10.7	HP
	5	25°30.90 : 69°10.97	9.1	HP
	6	25°30.91 : 69°11.01	4.9	HP
Rehmat Ali	7	25°29.28 : 69°11.78	7.6	HP
	8	25°28.81 : 69°11.34	7.6	MP
	9	25°28.89 : 69°11.46	7.6	MP
Suleman Rajar	10	25°31.11 : 69°08.98	4.6	HP
	11	25°31.18 : 69°09.17	6.1	HP
	12	25°31.08 : 69°08.96	7.6	MP
Dost Muhammad Mahar	13	25°29.76 : 69°06.73	4.6	MP
	14	25°29.91 : 69°06.62	4.6	HP
	15	25°29.83 : 69°06.69	4.6	MP
Wali Muhammad Rind	16	25°28.87 : 68°57.96	6.7	MP
	17	25°28.86 : 68°57.85	6.7	HP
	18	25°28.80 : 68°57.86	6.7	HP
Hussain Bux Mari	19	25°32.49 : 68°53.91	5.5	MP
	20	25°32.28 : 68°53.85	7.6	HP
	21	25°32.65 : 68°54.05	6.1	MP
Ameer Bux	22	25°39.57 : 69°07.21	6.1	HP
	23	25°39.60 : 69°07.15	6.7	HP
	24	25°39.59 : 69°07.12	9.1	HP
Chaudhry Nizam	25	25°22.90 : 69°01.88	9.1	MP
	26	25°22.87 : 69°01.87	9.1	HP
	27	25°23.14 : 69°01.88	6.1	HP
Gul Muhammad Rind	28	25°28.81 : 68°56.80	5.5	HP
	29	25°28.82 : 68°56.80	5.5	HP
	30	25°28.79 : 68°56.80	7.6	HP

Table 2. Parameters and their corresponding limits utilized in the calculation of quality measurements (qi). (Source: Meireles *et al*., 2010)

q_i	Na^+ mmol/L	Cl^- mmol/L	HCO_3^- mmol/L	SAR √mmol/L	EC µS/cm
0 - 35	<2 or ≥9	<1 or ≥10	<1 or ≥8.5	<2 or ≥12	<200 or ≥3000
35 – 60	6 to <9	7 to <10	4.5 to <8.5	6 to <12	1500 to <3000
60 – 85	3 to <6	4 to <7	1.5 to <4.5	3 to <6	750 to <1500
85 - 100	2 to <3	1 to <4	1 to <1.5	2 to <3	200 to <750

Cumulative effects of EC, RSC, and SAR on water quality

According to the classification of water based on the cumulative effects of three parameters—EC, RSC, and SAR—only 5 of the 30 samples (samples 3, 10, 12, 15, and 17) were classified as fit for use. Furthermore, an additional 5 samples (samples 1, 2, 11, 21, and 26) were categorized as marginally fit. The remaining 20 samples, constituting 66.67% of the total, were classified as unfit according to the suitability criteria outlined in Table 6 (Waheed *et al*., 2010).

Magnesium adsorption ratio (MAR)

Ca^{2+} and Mg^{2+} typically maintain a state of equilibrium in most groundwater systems (Möller and Lucia, 2020). When equilibrium is disrupted, an increased concentration of Mg^{2+} within groundwater can adversely affect soil quality, resulting in alkalinity and a subsequent decline in crop yield (Kumar *et al*., 2007). A magnesium hazard will likely develop when the Mg^{2+}-to-Ca^{2+} ratio exceeds 50 %. The severity of the detrimental effects correlates positively with the Mg^{2+} and Ca^{2+} ratio. Nevertheless, the negative impact of Mg^{2+} in irrigation water on soil may be mitigated by the dissolution of $CaCO_3$ present in the soil, which releases Ca^{2+}. The MAR values in the present study ranged from 30.51 to 86.59 meq/L, averaging 52.34 ± 10.61 meq/L (Table 4). with 56.67 % of the groundwater samples exceeding the permissible limit of 50 (Table 4). This indicates a potentially adverse effect on crop yield and an increase in soil alkalinity. The increased concentration of Mg^{2+} may be attributed to the dissolution of dolomite (Singh *et al*., 2020). Such samples may negatively influence crop production by promoting a more alkaline soil environment (Paliwal, 1972).

Table 3. Chemical parameters in mg/L except pH, EC in μS/cm, and irrigation water quality index (IWQI) for groundwater from Mirpur Khas district.

No.	pH	Na^+	K^+	Ca^{2+}	Mg^{2+}	HCO_3^-	Cl^-	SO_4^{2-}	EC	IWQI
1	8.5	102	6.4	80	36	210	95	215	1157	68.53
2	8.4	107	5.9	68	34	220	75	216	1112	82.85
3	8.6	46	4	48	27	180	45	78	676	78.71
4	8.4	224	10	60	68	400	185	255	1868	68.37
5	8.6	202	6.4	68	70	330	195	282	1818	61.91
6	8.7	152	4.6	64	78	370	191	167	1654	66.28
7	8.7	370	6.4	58	30	440	255	260	2180	33.02
8	8.5	248	5.5	56	51	380	195	234	1810	55.69
9	8.8	271	5.6	60	46	400	215	218	1887	52.59
10	8.8	36	4.2	24	15	100	45	32	410	66.26
11	8.2	108	7.3	60	44	310	85	116	1155	64.45
12	8.1	38	3.9	28	15	120	41	34	441	67.14
13	8.2	234	13.4	128	88	340	355	345	2430	49.93
14	8.2	370	6.5	128	70	390	271	630	2880	43.21
15	8.3	72	3.1	38	30	200	85	52	765	72.91
16	8.2	403	8.2	132	92	410	570	370	3210	40.69
17	8.7	61	6.5	28	32	180	68	58	689	77.78
18	8.4	206	9.2	36	141	410	310	260	2270	52.99
19	8.2	220	30	184	49	430	315	274	2360	50.95
20	8.4	248	6.8	180	71	330	230	610	2630	54.5
21	8.3	74	6.9	78	45	270	105	122	1123	68.03
22	8.1	302	24.2	144	102	480	385	410	2960	41.04
23	8.1	510	15.4	220	126	420	925	440	4410	31.09
24	7.8	790	33.8	268	168	460	1277	780	6270	43.63
25	8.1	168	8.2	80	61	300	241	174	1670	63.33
26	8.4	98	6.4	68	34	260	127	84	1075	63.07
27	8.3	258	5	68	56	330	195	340	1947	56.04
28	8	296	9.5	160	75	380	184	680	2740	52.29
29	8.3	240	8.5	172	61	350	304	410	2440	53.83
30	8.2	178	9.2	180	117	380	370	405	2670	40.16
Min.	7.8	36	3.1	24	15	100	41	32	410	31.09
Max.	8.8	790	33.8	268	168	480	1277	780	6270	82.85
Mean	8.4	221	9.4	99	64	326	265	285	2024	57.38
SD	0.2	159	7.4	64	37	102	262	197	1222	13.41

Table 4. Computed values of irrigation water quality parameters for the groundwater of Mirpur Khas district.

No.	Na%	SAR	MAR	RSC	PI	KR
1	39.81	2.38	42.60	-3.51	55.23	0.64
2	43.69	2.65	45.19	-2.59	60.42	0.75
3	31.29	1.32	48.12	-1.67	56.19	0.43
4	53.79	4.70	65.14	-2.03	67.11	1.13
5	49.44	4.11	62.93	-3.75	61.94	0.96
6	41.18	3.02	66.77	-3.55	55.93	0.69
7	75.19	9.83	46.03	1.85	87.52	3.00
8	60.98	5.77	60.03	-0.76	74.71	1.54
9	63.77	6.40	55.83	-0.22	77.28	1.74
10	40.75	1.42	50.75	-0.79	71.19	0.64
11	42.47	2.58	54.74	-1.53	61.45	0.71
12	39.97	1.44	46.90	-0.66	71.31	0.63
13	43.56	3.90	53.13	-8.06	52.67	0.75
14	57.24	6.53	47.42	-5.76	65.94	1.32
15	42.38	2.12	56.56	-1.09	65.93	0.72
16	55.61	6.59	53.47	-7.44	63.50	1.24
17	41.15	1.87	65.33	-1.08	65.40	0.66
18	40.70	3.46	86.59	-6.68	51.67	0.67
19	43.88	3.72	30.51	-6.17	53.65	0.72
20	42.51	3.96	39.41	-9.42	51.20	0.73
21	30.89	1.65	48.75	-3.17	49.22	0.42
22	46.88	4.71	53.87	-7.71	55.51	0.84
23	51.40	6.79	48.57	-14.46	56.99	1.04
24	56.43	9.32	50.83	-19.66	60.28	1.26
25	45.48	3.44	55.70	-4.10	58.37	0.81
26	41.68	2.42	45.19	-1.93	60.52	0.69
27	58.65	5.61	57.59	-2.59	70.47	1.40
28	48.10	4.84	43.60	-7.93	56.86	0.91
29	43.93	4.00	36.90	-7.87	53.38	0.77
30	30.00	2.54	51.73	-12.38	38.85	0.42
Min.	30	1.32	30.51	-19.66	38.85	0.42
Max	75.19	9.83	86.59	1.85	87.52	3
Mean	46.76	4.1	52.34	-4.89	61.02	0.94
SD	10.04	2.2	10.61	4.7	9.68	0.51

Sodium percentage (Na%)

Na% is widely utilized for evaluating the suitability of water for irrigation purposes (Wilcox, 1955). The Na% ranged from 30 to 75.19, with a mean value of 46.76 ± 10.04 (Table 4). The Na% values indicate that the water is categorized as 'good' (20 to 40 Na%), 'permissible' (40 to 60 Na%), and 'doubtful' (60 to 80 Na%). Based on this classification, 16.67% of the samples fell within the good category, 73.33% were within the permissible limit, and only 10% were doubtful (Table 5). Consequently, 90% of the groundwater samples were classified between good and permissible. When the concentration of Na^+ in irrigation water is elevated, Na^+ ions are inclined to be absorbed by clay particles, displacing Mg^{2+} and Ca^{2+}. This ion exchange process diminishes permeability and leads to poor internal drainage. The Wilcox (1955) diagram (Fig. **3**) relating Na% and EC indicates the following distribution of groundwater samples: 5 samples (3, 10, 12, 15, 17) fell into the 'excellent' category, 8 samples (1, 2, 5, 6, 11, 21, 25, 26) fell into the 'good' category, 4 samples (4, 8, 9, 27) were classified as 'admissible', 10 samples (7, 13, 14, 18, 19, 20, 22, 28, 29, 30) were categorized as 'doubtful', and 3 samples (16, 23, 24) fell into the 'bad' category. Overall, 56.67% of the groundwater samples were classified as excellent to admissible, while 43.33% were in the doubtful and bad categories. This suggests that most of the groundwater in the study area is suitable for irrigation.

Permeability index (PI)

The assessment of groundwater quality for irrigation suitability can be effectively conducted using PI values (Rawat *et al*., 2018). The concentrations of Ca^{2+}, Na^+, Mg^{2+}, and HCO_3^- significantly affect the permeability of the soil profile (Singh *et al*., 2015). These cations and anions are used to calculate the PI values of water to determine its quality. Additionally, Xu *et al*. (2019) established a correlation between higher PI values and increased Na^+ and HCO_3^- in groundwater. The increased levels of HCO_3^- and Na^+ may result from the dissolution of carbonate minerals, such as calcite and dolomite, alongside cation exchange processes. Nagaraju *et al*. (2006) classified water quality based on the PI into three categories: good (>75%), suitable (25% – 75%), and unsuitable (<25%). A high PI is often linked to subsurface structural features that can facilitate significant groundwater contamination. Based on the PI values, the groundwater samples from the study area fell within the suitable category (93.33%) and the good category (6.67%) (Table 5).

Irrigation water quality index (IWQI)

The IWQI ranged from 31.09 to 82.85, with an average value of 57.38 ± 13.41 (Table 3). Approximately 6.67% of the samples had severe irrigation (SR) restrictions (Table 4), meaning groundwater can only be used for irrigating plants with high salt tolerance. Additionally, 40% of the samples fell under the high restriction (HR) category, which poses serious risks to soil health and can harm or kill plants. To mitigate plant damage in these cases, salt leaching is necessary. Another 40% of the samples were identified as having moderate restrictions (MR), where mild salt leaching is recommended, especially in soils with moderate to high permeability. Finally, 13.33% of the samples were classified as having low restrictions (LR), indicating that irrigation can be effectively used in soils with a light texture or moderate permeability. However, caution should be exercised with heavy-textured soils, as they may become sodic and not recommended for use in areas with high salinity. The results suggest that the low IWQI values observed in some wells could be attributed to the elevated levels of EC, SAR, and Na^+ associated with water quality classes.

Table 5. Classification of groundwater for irrigation purposes based on various parameters.

Parameters	Range	Classification	No. of samples	%
EC (µS/cm)	<250	Excellent	0	0.00
	250 - 750	Good	4	13.33
	750 - 2000	Permissible	13	43.33
	2000 - 3000	Doubtful	10	33.33
	>3000	Unsuitable	3	10.00
SAR	<10	Excellent	30	100
	10 – 18	Good	0	0
	18 – 26	Doubtful	0	0
	>26	Unsuitable	0	0
RSC	<1.25	Good	29	96.67
	1.25 - 2.5	Doubtful	1	3.33
	>2.5	Unsuitable	0	0
Na%	<20	Excellent	0	0.00
	20 – 40	Good	5	16.67
	40 – 60	Permissible	22	73.33
	60 – 80	Doubtful	3	10.00
	>80	Unsuitable	0	0.00
PI (%)	>75	Good	2	6.67
	25 – 75	Suitable	28	93.33
	<25	Unsuitable	0	0.00
MR	<50	Suitable	13	43.33
	>50	Unsuitable	17	56.67
IWQI	80 – 100	No restriction	0	0.00
	70 – 85	Low restriction	4	13.33
	55 – 70	Moderate restriction	12	40.00
	40 – 55	High restriction	12	40.00
	0 – 40	Severe restriction	2	6.67

Table. 6. The criteria for determining the suitability of irrigation water (Waheed *et al.*, 2010).

Parameter	Fit	Marginally fit	Unfit
EC (µS/cm)	<1000	1000 - 1250	>1250
RSC (meq/L)	<1.25	1.25 – 2.25	>2.25
SAR (mmol/L)	<6	6 - 10	>10

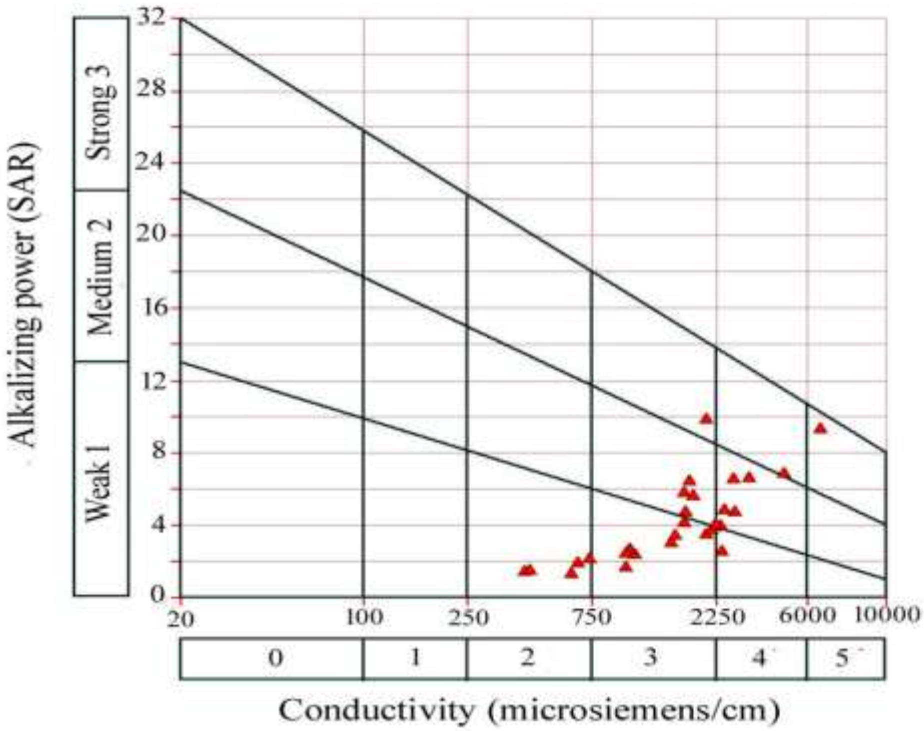

Fig. 2. US salinity diagram, classifying groundwater samples from the Mirpur Khas district based on sodium adsorption ratio (SAR) and electrical conductivity (EC).

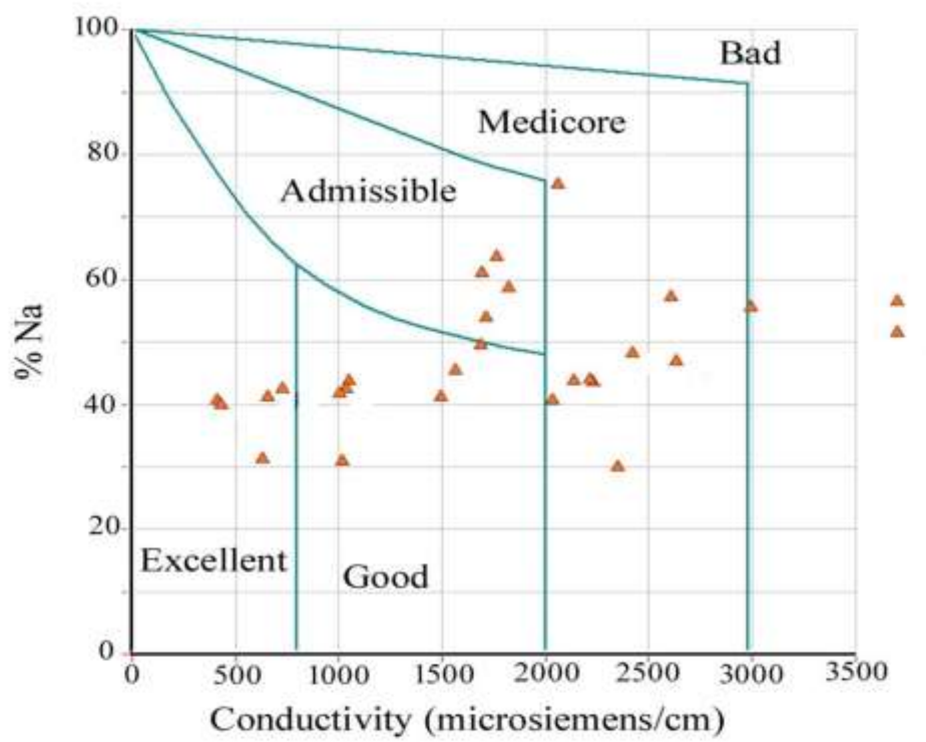

Fig. 3. Wilcox's diagram classifying groundwater samples from the Mirpur Khas district based on the percent of sodium (%Na) and electrical conductivity (EC).

CONCLUSION

The assessment of various indicators for groundwater irrigation quality generally indicates that the water is suitable for irrigation. However, some samples showed unsuitability for this use. The IWQI revealed that 53% of the water samples fell into the 'low' to 'moderate restriction' categories, while 47% were classified as 'high' to 'severe restriction' categories. According to the average IWQI values, the water from Amer Bux village was categorized as having 'severe restrictions.' In contrast, samples from Rehmat Ali and Gul M. Rind villages were classified under the 'high restriction' category. Only one water sample from H.F.K. Lashari village was categorized as 'low restriction.' The remaining seven villages' samples were assessed in the 'moderate restriction' category. The study underscores the importance of implementing comprehensive water quality monitoring protocols, developing crop varieties with enhanced salinity resistance, and instituting measures to mitigate groundwater contamination.

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