INVESTIGATION OF SEASONAL WATER QUALITY IN WETLANDS OF JHAJJAR DISTRICT (HARYANA), INDIA AND SUITABILITY FOR DRINKING AND AGRICULTURAL USE

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Original scientific paper
Received: September 21st, 2024
Accepted: November 17th, 2024
HAE-2499
https://doi.org/10.33765/thate.15.3.1

ABSTRACT

Surface freshwater bodies are essential for drinking and irrigation, but rapid development and industrial activities pollute these precious resources. This study investigates seasonal fluctuations in water quality and its suitability for drinking and agriculture in the wetlands of Jhajjar district (Haryana), India. Seventy-five water samples were collected from 25 locations during the pre-monsoon, monsoon, and post-monsoon seasons and tested for physicochemical parameters such as pH, electrical conductivity (EC), total dissolves solids (TDS), turbidity, sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), chloride (Cl^-), sulphate (SO_4^{2-}), carbonate (CO_3^{2-}), and bicarbonate (HCO_3^-) ions. The one-way repeated measures analysis of variance (ANOVA) revealed significant differences ($p < 0.05$) in the means of most of the water parameters during different seasons. The water quality index (WQI) revealed that more than 85 % of the samples were unfit for consumption. Irrigation indicators such as sodium absorption ratio (SAR), sodium percentage (Na%), and residual sodium carbonate (RSC) suggested the appropriateness of samples for agricultural use. However, the magnesium hazard (MH) index and US salinity laboratory (USSL) diagram suggested that many samples were unsuitable for irrigation. The Piper trilinear diagram showed that Ca^{2+}-Mg^{2+}-HCO_3^- type water was predominant in all seasons, while the Gibbs plot identified evaporation and rock-water interactions as the primary factors influencing water chemistry. Principal component analysis (PCA) indicated TDS, EC, and Cl^- as key drivers of water quality, while cluster analysis divided sampling locations into four primary groups. This study emphasizes the critical need for sustainable water management interventions and solutions to maintain public health and the long-term sustainability of agriculture.

Keywords: *surface water quality, wetlands, seasonal variation, drinking and irrigation suitability, water quality index*

INTRODUCTION

Freshwater reservoirs and wetlands are dynamic biological systems that create biomass and support various plant and animal life [1]. Wetlands, which comprise ponds, rivers, and lakes, connect terrestrial and aquatic ecosystems due to their shallow water coverage and near-surface water table [2, 3]. These wetlands, particularly in India, largely depend on the monsoon season, which is essential for maintaining their hydrology, supporting diversified ecosystems, and ensuring the sustainability of agricultural practices in the surrounding areas [4]. The Indian monsoon, the largest in the world, plays a vital influence in shaping India's aquatic habitats [5] by delivering over 70 % of the country's annual rainfall, predominantly in June and July, irrigating 60 % of India's agricultural land and water bodies. Wetlands provide valuable ecological services such as groundwater recharge, flood management, nutrient storage, and carbon sequestration [6]. Furthermore, lentic wetlands such as ponds and lakes sequester more carbon than grasslands, forests, and oceans, demonstrating their importance in maintaining equilibrium of atmospheric carbon dioxide (CO_2) [7]. Wetlands that are a part of surface freshwater resources are also essential for various applications, including drinking and irrigation, because they are more accessible than groundwater [8]. In villages, ponds serve as central wetlands that offer eco-hydrological benefits while fulfilling various other ecological and economic roles [9, 10]. Despite this, anthropogenic activities continue to threaten surface freshwater supplies [11]. Household pollutants, industries, sewage, and agricultural runoff contaminate these water bodies, changing their chemistry and causing ecosystem deterioration [12]. In rural regions, pollutants such as heavy metals, microplastics, soaps, detergents, cow dung, and human faeces significantly affect wetland water quality [11]. Pollution from these sources reduces access to clean and fresh water in many parts of India, leading to concerns about water safety. In 2010, the United Nations General Assembly recognized the global importance of clean water by designating access to safe drinking water as a fundamental human right [13]. Although 85 % of India's urban population has access to safe drinking water, increased demand, particularly in agriculture, raises concerns about future water supply [14]. It is expected that two-thirds of the world's population will face water scarcity by 2025, emphasizing the importance of carefully assessing the quality of water for drinking and agricultural uses [15]. Water quality indicators, consisting of physical, chemical, and biological components, are crucial for assessing the health of water bodies, particularly in rural areas where surface water is a key resource. Research gaps exist in the assessment of water quality in rural wetlands, particularly regarding seasonal fluctuations and their impacts on agricultural output in southern Haryana. Previous studies have evaluated specific contaminants in water [16 - 18], but complete and seasonal assessments in the region remain underexplored. Given that irrigation consumes the most freshwater globally [19], poor water quality affects water resources and human health, impairs soil quality, and reduces crop yields [20]. Therefore, monitoring the quality of drinking and irrigation water is imperative for ensuring sustainable water management. This study seeks to fill the research gap by analysing surface water for drinking and irrigation in the Jhajjar district, providing significant insights for improved water resource management. The objectives of the study are: a) quantification of the physicochemical parameters of surface water in selected wetlands of Jhajjar district and b) examination of seasonal fluctuations in physicochemical parameters using various indices and applying different statistical methods.

EXPERIMENTAL

Study area

Haryana is one of the states in northern India. It forms Delhi's northern, southern, and western borders and surrounds the capital on three sides. Jhajjar, one of the 22 districts in the state, is located in the southeast at the coordinates 28.6071° N latitude and 76.6569° E longitude (Figure 1).

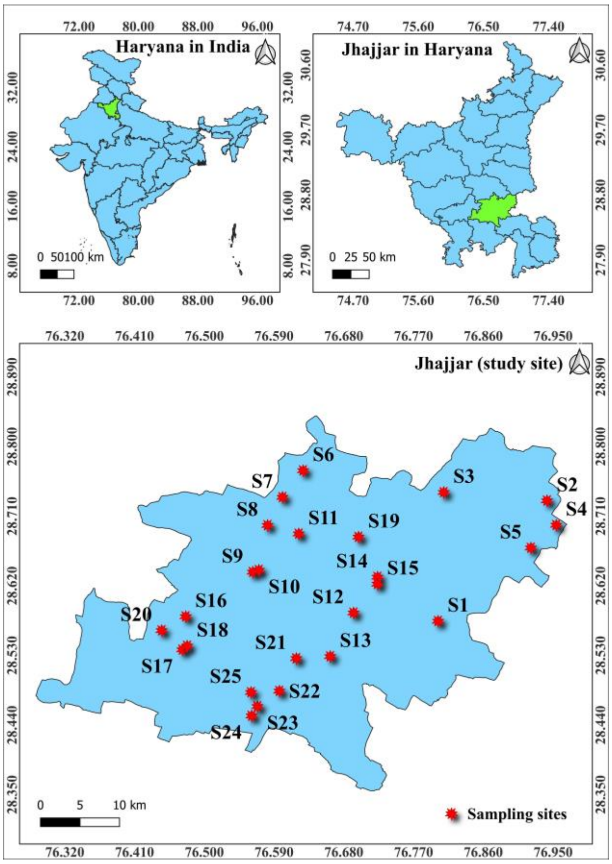

Figure 1. Map of the study area

The district's geographical area is 1834 km^2, which constitutes 3.77 % of Haryana's total area and has a population density of 523 persons per km^2. The district headquarters is located in Jhajjar City, 65 km from the country's capital. The current population of Jhajjar district is 958405, of which 514667 are males and 443738 are females. The district's population has grown by 8.90 % [21]. The Jhajjar district is administratively organized into five community development blocks: Beri, Bahadurgarh, Jhajjar, Matanhail, and Salhawas. The district has 250 Gram Panchayats and 263 revenue villages. Each village has numerous village ponds. These sites are known locally as Johar, Talab, Talav, Tal, and Pokher. Located at an altitude of 214.17 m above sea level, Jhajjar has a subtropical steppe climate (Classification: BSh). The district's average annual temperature is 31.06 ºC, which is 5.09 % higher than India's averages. Jhajjar receives about 627 mm of precipitation annually [22]. The lithological correlation shows the presence of sand and clay layers on the upper soil surface.

Sample collection and analysis

In 2017, 25 sampling locations in the Jhajjar district were selected for collecting water samples (Figure 1). Samples were collected from all five blocks in the Jhajjar area, and five sites were selected from each block. At each location, five replicates were collected. The samples were collected during three seasons: pre-monsoon (March - May), monsoon (June - September), and post-monsoon (October - December); overall, 75 samples (25 in each season) were collected during three seasons. The geographic coordinates and details of sampling sites are presented in Table 1.

Table 1. Sample locations and geographic data

Sample No.	Block	Village name	Wetland name	Latitude	Longitude
S1	Bahadurgarh	Badli	Rabsar	28.57440	76.80159
S2		Bamnoli	Gaonwala	28.73012	76.94222
S3		Rodh	Germawala	28.74093	76.80894
S4		Parnala	Shivemandir	28.69855	76.95417
S5		Balore	Mandirwala	28.66907	76.92138
S6	Beri	Dighal	Bhorsa	28.76908	76.62753
S7		Gochhi	Mokhri	28.73456	76.60092
S8		Beri	Tulyan	28.69828	76.58169
S9		Jhajgarh	Tala	28.63786	76.56256
S10		M.P.Majra	Pilsan	28.64031	76.57042
S11	Jhajjar	Dujana	Nya	28.68731	76.62186
S12		Shikanderpur	Gaonwala	28.58511	76.69258
S13		Raipur	Dadawala	28.52875	76.66250
S14		Bhadani	Bada	28.63142	76.72350
S15		Kablana	Mandirwala	28.62239	76.72350
S16	Matanhail	Matanhail	Peelkhudana	28.58033	76.47603
S17		Amadal-Sahpur	Johri	28.53750	76.47178
S18		Mundsa	Tala	28.54233	76.47786
S19		Akeri-Madanpur	Schoolwala	28.68320	76.69900
S20		Rudiawas	Medhawala/ Nyajo-har	28.56232	76.44498
S21	Salhawas	Surehti	Bada	28.52614	76.61875
S22		Samaspur-Majra	Ghamdi	28.48406	76.59689
S23		Subana	Tala	28.46414	76.56861
S24		Girdharpur	Sirjawala	28.45199	76.56108
S25		Dhakla	Puranmal	28.48233	76.56031

Samples were collected 15 - 30 cm below the surface in clean, disinfected plastic bottles (2 litres) filled to the top and immediately sealed [23]. Every bottle was neatly labelled with the sample number S1, S2, S3, …., and S25, date, time, and location. Refrigeration and other immediate preservation procedures were used when necessary. During transport, samples were stored in a box with ice packs to maintain the temperature at 4 °C and delivered to the laboratory within 24 hours [24]. Before analysis, all samples were filtered via Whatman filter paper (Grade 42) to remove all undesired solid and suspended impurities.

The following physical parameters were measured: pH, turbidity, electrical conductivity (EC), and total dissolved solids (TDS). Cations such as sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}), and anions such as chloride (Cl^-), sulphate (SO_4^{2-}), carbonate (CO_3^{2-}), and bicarbonate (HCO_3^-) were analysed. The physicochemical analysis of water samples was performed using standard analytical procedures [24].

Water quality index (WQI)

The water quality index (WQI) is a grading system that considers the cumulative effects of multiple water quality parameters. The WQI calculation simplifies complex water quality data into understandable and practical information. The WQI was calculated using the previously described procedure [25].

The following steps were involved in calculating the WQI:

Step 1: Selected water parameters, such as pH, EC, TDS, Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, and HCO_3^- were assigned weights (wi) according to their relative importance (from 1 to 5) in the overall drinking water quality [26] (Table 2).

Table 2. Permissible limits, assigned and relative weights

Parameters	Bureau of Indian standards (BIS 2012)	Assigned weight (AW)	Relative weight (RW) $RW=\frac{AW}{\sum_{i=1}^{n} AW}$
pH	6.5 - 8.5	4	0.11428
TDS (mg/L)	500	5	0.14285
EC (µS/cm)	-	3	0.08571
Na^+ (mg/L)	-	4	0.11428
K^+ (mg/L)	-	2	0.05714
Ca^{2+} (mg/L)	75	3	0.08571
Mg^{2+} (mg/L)	30	3	0.08571
Cl^- (mg/L)	250	5	0.14285
SO_4^{2-} (mg/L)	200	5	0.14285
HCO_3^- (mg/L)	200	1	0.02857
		$\sum$ AW= 35	$\sum$ RW = 1

The calculation of the relative weight (RW) of the chemical parameter involved the use of the assigned weight (AW) according to the following equation:

$$RW=\frac{AW}{\sum_{i=1}^{n} AW} \qquad (1)$$

where is: RW - relative weight, AW - assigned weight.

Step 2: The quality rating scale (Q) for each parameter was designed following the Indian standard [27] by dividing its concentration in each water sample by its corresponding standard value. Each parameter was given a quality rating using the following equation:

$$Q=[C_i/S_i]\times 100 \qquad (2)$$

For pH, the following equation was used:

$$Q=\left[\frac{C_i - V_i}{S_i - V_i}\right]\times 100 \qquad (3)$$

where is: Q - quality rating, C_i - concentration of specific parameters in the water sample, S_i -

recommended value for specific parameter, V_i - ideal value (7 for pH).

Step 3: The Sub-indices (SI) were then calculated to obtain the WQI:

$$SI = RW \times Q \quad (4)$$

$$WQI = \sum_{i=n-1}^{n} SI \quad (5)$$

The value of WQI usually ranges from 0 to 301 with various sub-classes. The water quality was classified according to the ranges available in the literature [28]: excellent water (WQI < 50), good water (WQI = 51 - 100), poor water (WQI = 101 - 200), very poor water (WQI = 201 - 300), and unsuitable for drinking (WQI > 300).

Irrigation suitability and hydro-chemical evaluation

The following parameters were used to assess irrigation quality and determine the suitability of surface water: sodium absorption ratio (SAR), sodium percentage (Na%), residual sodium carbonate (RSC), permeability index (PI) [29], Kelly's ratio (KR) [30], and magnesium hazard (MH).

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} \quad (6)$$

$$Na\% = \frac{Na^{+} + K^{+} \times 100}{Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}} \quad (7)$$

$$RSC = \left[\left(CO_3^{2-} + HCO_3^{-}\right) - \left(Ca^{2+} + Mg^{2+}\right)\right] \quad (8)$$

$$PI = \frac{Na^{+} + \sqrt{HCO_3^{-}}}{Na^{+} + Ca^{2+} + Mg^{2+}} \times 100 \quad (9)$$

$$KR = \frac{Na^{+}}{Ca^{2+} + Mg^{2+}} \quad (10)$$

$$MH = \frac{Mg^{2+}}{Ca^{2+} + Mg^{2+}} \times 100 \quad (11)$$

Apart from these, the suitability of water samples for irrigation and their hydro-chemical evaluation was interpreted using the US salinity laboratory (USSL) plot [31], Wilcox diagram [32], Piper trilinear plot [33], and Gibbs plot [34].

Graphing and statistical analysis

The maps for spatial distribution of WQI were created using QGIS 3.16.0 with GRASS 7.8.4 software. These maps were plotted with an interpolation function using inverse weight distance, and the coefficient value used was 2.0. The statistical differences in physicochemical parameters between the seasons were examined using one-way repeated measures analysis of variance (ANOVA) and pairwise comparison by Tukey's grouping letters. Principal component analysis (PCA) is generally used to reduce the dimensionality of large data sets by dividing a large collection of variables into smaller variables for easier understanding. Before PCA analysis, the Kaiser Meyer Olkin (KMO) test [35] and Bartlett's test [36] of sphericity were conducted to measure the sampling adequacy and correlation among variables, as used previously [37]. A KMO value below 0.50 is unacceptable and indicates that sampling is inadequate, and a p-value < 0.05 from Bartlett's test indicates that variables are correlated enough to conduct the analysis. The results of the Kaiser-Meyer-Olkin (KMO) and Bartlett's tests for conducting PCA are presented in Table 3. During all the seasons, pre-monsoon (0.61), monsoon (0.76), and post-monsoon (0.67), the KMO values exceed the permissible threshold of 0.50, indicating sampling adequacy. Bartlett's test results revealed significant Chi-square values (p < 0.00), suggesting that the correlation matrices for each season are not identity matrices. This indicates that the variables are sufficiently correlated to proceed with PCA for each season.

PCA was performed using SPSS 25.0. Hierarchical cluster analysis (HCA) groups the parameters so that items in a similar group (called a cluster) are more comparable than those in dissimilar groups (clusters). A dendrogram is a graph that shows clusters of different parameters. A dendrogram was constructed for samples in various seasons using SPSS 25.0.

Table 3. KMO and Bartlett's tests for measuring sampling adequacy and correlation among parameters

Season	KMO value	Approx. Chi-square	Degrees of freedom (*df*)	*p*-value
Pre-monsoon	0.61	361.58	55	< 0.00
Monsoon	0.76	370.99	55	< 0.00
Post-monsoon	0.67	313.48	55	< 0.00

RESULTS AND DISCUSSION

Table 4 shows a statistical overview of different water parameters during different seasons. It presents the minimum, maximum, and mean values and their corresponding standard deviations for each parameter observed throughout these seasons. The significant difference among means of different parameters was assessed using a one-way repeated measures ANOVA, which provides F-values for each parameter. The results were compared with the World Health Organization (WHO) [38] and Indian Standard 10500 [27] for their suitability (Table 5).

Physical parameters

The pH values of samples varied from 7.4 - 8.8 (pre-monsoon), 6.8 - 8.7 (monsoon), and 6.9 - 8.6 (post-monsoon). During pre-monsoon season, S5, S16, and S22 had the highest pH (8.8), while S1 had the lowest (6.8). Lower pH during the monsoon season could be due to higher turbidity and temperature. This turbidity can reduce sunlight penetration, decreasing the rate of photosynthesis in aquatic plants. Photosynthesis usually consumes CO_2, which acts as a weak acid when dissolved in water. The reduction in photosynthesis results in higher levels of free CO_2, leading to a drop in pH [39]. Turbidity in samples varied depending on the season: pre-monsoon (4.6 - 112.0 NTU), monsoon (3.8 - 97.6 NTU), and post-monsoon (4.9 - 95.8 NTU).

Table 4. Statistical overview of various water parameters in different seasons

Physicochemical parameters, ions & different indices	Pre-monsoon season			Monsoon season			Post-monsoon season			One-way repeated measures ANOVA between seasons
	Min	Max	Mean±SD	Min	Max	Mean±SD	Min	Max	Mean±SD	*F*-value
pH	7.4	8.8	8.06±0.4a	6.8	8.7	7.4±0.4b	6.9	8.6	7.7±0.4c	26.3*
Turbidity (NTU)	4.6	112.0	40.22±33.1a	3.8	97.6	37.46±32.2b	4.9	95.8	36.72±30.5b	7.7*
TDS (mg/L)	271	5991	2316.08±1671.2a	216	5980	2223.28±1626.9b	253	5510	2212.72±1579.9b	5.7*
EC (µS/cm)	420	8950	3476.76±2478.5a	325	8945	3332.40±2423.1b	386	9240	3360.48±2434.8c	5.3*
Na^+ (mg/L)	43.0	348.0	184.8 ±102.9a	32.0	320.0	169.2±101.0b	41.0	300.0	168.8±95.1b	13.3*
K^+ (mg/L)	20.0	332.0	135.7±92.0a	17.0	314.0	122.1±88.2b	23.0	327.0	124.8±86.4b	15.5*
Ca^{2+} (mg/L)	26.0	641.2	119.9±123.3a	20.7	486.9	92.0±94.6b	20.0	617.6	104.8±116.2b	10.3*
Mg^{2+} (mg/L)	39.5	325.0	161.4±85.5a	29.6	305.0	143.4±86.6b	32.2	272.0	147.5±85.1b	38.1*
Cl^- (mg/L)	56.8	2277.0	819.17±554.6a	99.4	2238.0	656.0±497.7b	57.2	2174.0	715.3±523.0b	14.8*
SO_4^{2-} (mg/L)	68.0	496.1	230.1±110.3a	37.1	456.0	187.6±104.2b	37.7	440.0	192.3±108.7b	27.3*
CO_3^{2-} (mg/L)	BDL	54.0	7.7±16.3a	BDL	36.0	3.6±9.0b	BDL	36.0	3.1±9.2b	4.5*
HCO_3^- (mg/L)	236.8	980.0	437.0±212.5a	219.6	805.2	394.5±177.7b	212.8	840.0	367.9±168.1b	12.3*
WQI	80.2	626.4	286.5±145.4a	41.6	580.8	244.3±142.0b	59.9	589.0	255.1±141.0c	127.5*
SAR	4.9	31.9	16.0±8.2a	4.3	32.4	16.0±8.4a	4.7	33.7	15.7±8.2a	0.3
Na% (meq/L)	9.0	43.6	26.2±9.0a	8.3	48.3	27.6±10.0ab	8.8	50.1	27.0±10.0b	3.5*
KR (meq/L)	0.1	1.2	0.6±0.3a	0.1	1.2	0.5±0.3b	0.1	1.4	0.5±0.3b	21.2*
MH (meq/L)	45.5	89.0	70.4±11.7a	50.8	86.9	72.1±11.1a	45.9	90.1	71.2±11.0a	1.1
RSC (meq/L)	-53.9	1.8	-11.8±12.4a	-45.0	5.1	-9.8±11.1b	-53.4	3.1	-11.2±12.0b	10.0*
PI (meq/L)	16.1	65.5	42.9±12.7a	17.2	76.0	47.3±15.6b	16.2	77.2	44.8±14.8b	9.2*

* Means are significantly different at $p < 0.05$. The means in the same row that do not share a letter differ significantly. (Min - minimum, Max - maximum, SD - standard deviation, BDL - below detection level)

Table 5. The values of physicochemical parameters according to drinking water standards (WHO and IS-10500)

Parameters	WHO (2012)		IS-10500 (2012)	
	Desirable	Not permissible	Desirable	Not permissible
pH	6.5 - 8.5	< 6.5 and > 8.5	6.5 - 8.5	> 8.5
Turbidity (NTU)	2.5 -5	> 5	1 - 5	> 5
TDS (mg/L)	< 500	> 1500	500	> 2000
EC (µS/cm)	< 500	> 1500	--	--
Na^+ (mg/L)	< 200	> 600	--	--
K^+ (mg/L)	< 10	> 10	--	--
Ca^{2+} (mg/L)	< 75	> 200	75	> 200
Mg^{2+} (mg/L)	< 50	> 150	30	> 100
Cl^- (mg/L)	< 250	> 500	250	> 1000
SO_4^{2-} (mg/L)	< 200	> 250	200	> 400
CO_3^{2-} (mg/L)	--	--	--	--
HCO_3^- (mg/L)	< 300	> 600	--	--

In the pre-monsoon season, S8 had the highest turbidity value (112.0 NTU), while S15 had the lowest (3.8 NTU) during the monsoon season. The highest levels occur in pre-monsoon season (similar to results obtained by previous studies), primarily due to the accumulation of suspended sediments from previous dry periods, which remain in suspension due to low water flow [40, 41]. These seasonal fluctuations highlight the influence of rainfall and runoff on water clarity. TDS values ranged from 271 - 5991 mg/L during pre-monsoon, 216 - 5980 mg/L during the monsoon, and 253 - 5510 mg/L during post-monsoon season. The highest TDS was recorded in S23 (5991 mg/L) during the pre-monsoon season, perhaps due to active construction near the pond, increasing the discharge of dissolved solids. The lowest TDS was recorded in S20 (216 mg/L) during monsoon season, probably due to dilution from heavy rains. EC varied from 420 - 8950 µS/cm in the pre-monsoon, 325 - 8945 µS/cm during the monsoon, and 386 - 9240 µS/cm after the monsoon season. During the monsoon season, S20 had the lowest EC (325 µS/cm), most likely due to dissolved ions being diluted by rainfall.

The maximum EC was recorded in S23 during the post-monsoon season (9240 µS/cm), which is attributed to increased evaporation, reduced water volume, and concentrating ions. The means of all physical parameters were significantly different ($p<0.05$) between seasons. Furthermore, apart from pH, values of other parameters in more than 80 % of the samples were outside the permissible levels.

Cations

The Na^+ levels in the water samples ranged from 43 - 348 mg/L during the pre-monsoon, 32 - 320 mg/L during the monsoon, and 41 - 300 mg/L during the post-monsoon season. The highest Na^+ concentration was recorded in S5 during pre-monsoon season (348 mg/L), probably due to reduced dilution and increased evaporation. The lowest Na^+ level was observed in S20 during the monsoon season (32 mg/L). Na^+ concentrations in water samples show seasonal variability due to weathering, runoff, and evaporation [42]. In the pre-monsoon season, K^+ levels were at the highest level (332 mg/L in S12), probably due to intensified mineral weathering from rocks and soils rich in K^+. During the monsoon season, K^+ levels drop, with the lowest concentration in S15 (17 mg/L). During the post-monsoon season, levels (23 - 327 mg/L) rise again as evaporation continues, although residual rainfall continues to moderate concentrations. The geochemistry of local soils and hydrological parameters also contribute to these variations. The Ca^{2+} values ranged from 26.0 - 641.2 mg/L during pre-monsoon, 20.7 - 486.9 mg/L during the monsoon, and 20.0 - 617.6 mg/L during post-monsoon season. The highest concentration (641.2 mg/L in S23) in pre-monsoon season was probably due to evaporation, concentrating Ca^{2+} from geological sources such as limestone and gypsum [43]. The lowest concentration (20.7 mg/L in S16) occurred during the monsoon season, which can be attributed to excessive rainfall, diluting Ca^{2+}. Mg^{2+} concentrations in water samples varied from 39.5 - 325.0 mg/L in the pre-monsoon, 29.6 - 305.0 mg/L during the monsoon, and 32.2 - 272.0 mg/L in the post-monsoon season. In the pre-monsoon season, S23 had the highest Mg^{2+} content (325.0 mg/L), probably due to evaporation, concentrating Mg^{2+} from weathered materials such as dolomite and silicate. The means of all cations significantly varied ($p < 0.05$) between the seasons. Approximately 50 % of samples across seasons had values outside the permissible limits for Na^{+}, Ca^{2+}, and Mg^{2+}. Except for a few samples, K^{+} values were outside the desirable limits.

Anions

$Cl^{–}$ concentrations varied from 56.8 - 2277.0 mg/L during the pre-monsoon, 99.4 - 2238.0 mg/L during the monsoon, and 57.2 - 2174.0 mg/L during the post-monsoon season. During pre-monsoon season, water sample S23 had the highest $Cl^{–}$ concentration (2277 mg/L), and S20 had the lowest (56.8 mg/L). Excessive $Cl^{–}$ levels may indicate agricultural runoff or wastewater contamination, which could affect drinking water quality and crop irrigation [44]. The $SO_4^{2–}$ levels varied from 68.0 - 496.1 mg/L during the pre-monsoon, 37.1 - 456.0 mg/L during the monsoon, and 37.7 - 440.0 mg/L during the post-monsoon season. Sample S8 had the highest $SO_4^{2–}$ content (496.1 mg/L during the pre-monsoon season), while S1 had the lowest (37.1 mg/L during the monsoon season). Elevated $SO_4^{2–}$ levels can result from fertilizer use or natural deposition and leaching, potentially affecting the taste of water and increasing soil salinity [45], which can affect agricultural output. $CO_3^{2–}$ concentrations during the pre-monsoon, monsoon, and post-monsoon periods varied from BDL to 54 mg/L, BDL to 36 mg/L, and BDL to 36 mg/L, respectively. The highest $CO_3^{2–}$ concentration (54 mg/L) was recorded in sample S6 during the pre-monsoon season, but most samples did not show detectable values. $CO_3^{2–}$ levels usually fluctuate due to variables such as limestone decomposition or the buffering capacity of water [46]. Low $CO_3^{2–}$ or BDL also signals inadequate alkalinity, which can compromise the water's ability to neutralize acids and maintain a steady pH for agricultural usage. $HCO_3^{–}$ concentrations in water samples varied from 236.8 - 980.0 mg/L during the pre-monsoon, 219.6 - 805.2 mg/L during the monsoon, and 212.8 - 840.0 mg/L during the post-monsoon season. During the pre-monsoon period, sample S12 had the highest value (980 mg/L), and S20 had the lowest (236.8 mg/L). The $HCO_3^{–}$ contributes significantly to buffering capacity of water, controlling pH and protecting against acidification. Higher $HCO_3^{–}$ levels indicate significant mineral content, generally due to the weathering of carbonate rocks. This promotes both drinking water safety and agricultural use by reducing excessive acidity in the soil [47]. The means of all anions were significantly different ($p < 0.05$) between the seasons. The $Cl^{–}$ values in almost all the samples were within acceptable limits. Approximately 50 % of the samples had $SO_4^{2–}$ levels above allowed limits, while almost all samples had $HCO_3^{–}$ values above acceptable levels.

WQI

The WQI varied between seasons; in the pre-monsoon season, it was between 80.2 and 626.4, in the monsoon season between 41.6 and 580.8, and in the post-monsoon season between 59.8 and 589.0 (Figure 2a - 2c). Twelve percent of samples in the pre-monsoon season were rated as "good," 20 % as "poor," 20 % as "very poor," and 48 % as unfit for human consumption. During the monsoon season, 8 % of samples were "excellent," 16 % "good," 16 % "poor," 20 % "very poor," and 40 % unsuitable for drinking. During the post-monsoon season, 24 % of samples were rated as "good," 12 % as "poor," 20 % as "very poor," and 44 % as inappropriate for consumption. Site S23 had the highest WQI value (626.4) during the pre-monsoon season, whereas site S20 had the lowest value (45.5) during the monsoon season. These results show noticeable seasonal and spatial variations in the quality of the water, which are probably caused by various factors, including lower water volume and higher concentrations of pollutants during the dry period before the monsoon season, dilution and influx of pollutants from runoff during the monsoon rains, and residual contamination from rural and agricultural activities after the monsoon season.

Irrigation suitability and hydro-chemical evaluation

Irrigation water quality is vital for agricultural production, as it directly affects soil health, crop output, and long-term sustainability. Key parameters, such as SAR, Na%, KR, MH, RSC, and PI determine whether water is acceptable for irrigation. The suitability of water samples for irrigation was determined through various indices and plots.

SAR: The SAR values ranged from 4.9 - 31.9 in the pre-monsoon, 4.3 - 32.4 in the monsoon, and 4.7 - 33.7 in the post-monsoon season (Figure 3a - 3c). It has been previously stated that SAR values < 10 are suitable for irrigation [31]. Only 36 % of water samples from the study area met this criterion, and were considered suitable for irrigation.

Na%: Na% values in the study area ranged from 9.0 - 43.6 meq/L during the pre-monsoon, 8.3 - 48.3 meq/L during the monsoon, and 8.8 - 50.1 meq/L during the post-monsoon season (Figure 3d - 3f). During the seasons, only 10.6 % of samples had excellent Na% levels and were suitable for irrigation.

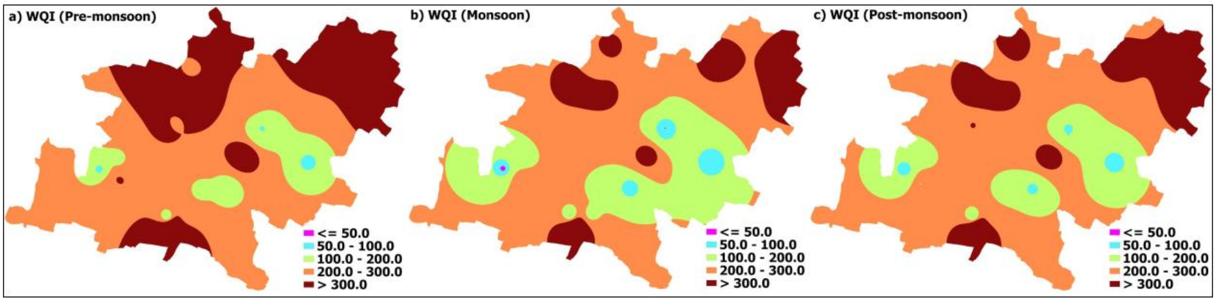

Figure 2. a) WQI in pre-monsoon, b) WQI in monsoon, and c) WQI in post-monsoon season

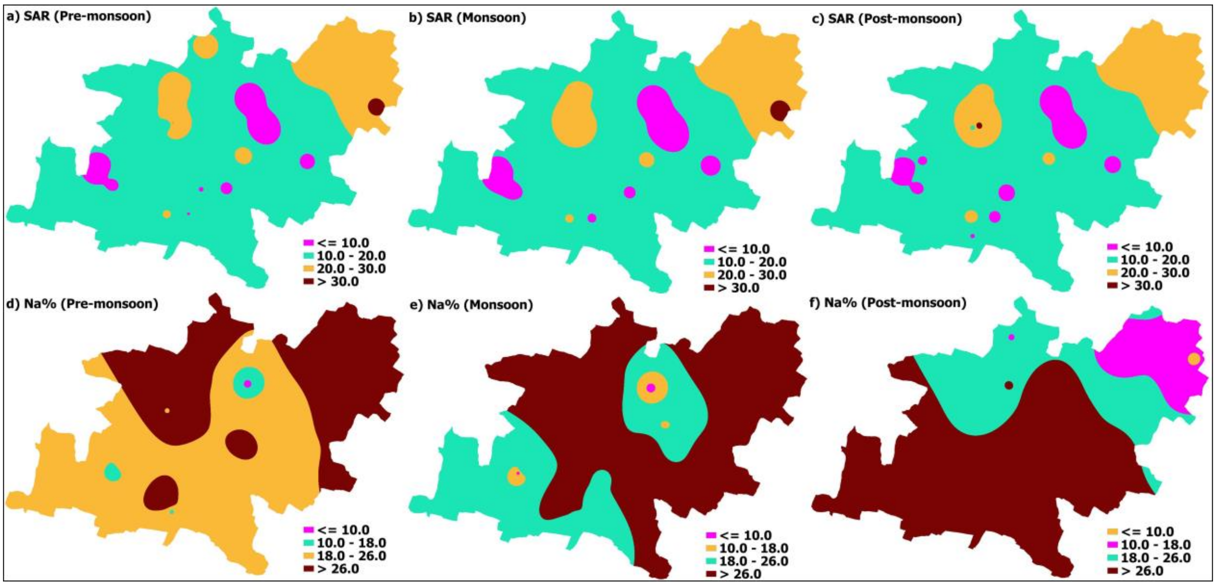

Figure 3. a) SAR in pre-monsoon, b) SAR in monsoon, c) SAR in post-monsoon, d) Na% in pre-monsoon, e) Na% in monsoon, and f) Na% in post-monsoon season

KR: KR varied from 0.1 - 1.2 meq/L during the pre-monsoon, 0.1 - 1.2 meq/L during the monsoon, and 0.1 - 1.4 meq/L during the post-monsoon season (Figure 4a - 4c). Water with a KR >1 is considered unsuitable for irrigation. Approximately 85 % of the samples were suitable for irrigation.

MH: MH values varied from 45.5 - 89.0 meq/L during the pre-monsoon, 50.8 - 86.9 meq/L during the monsoon, and 45.9 - 90.1 meq/L during the post-monsoon season (Figure 4d - 4f). Water samples with MH values above 50 meq/L are considered unsuitable for irrigation [48]. Based on spatial distribution, almost all samples were unsuitable for irrigation.

RSC: Except for site S16, where the RSC value exceeded 1.25 meq/L, all water samples had RSC values below 1.25 meq/L and were considered safe for irrigation without harmful effects (Figure 5a - 5c), based on the two-point scale classification (< 1.25 meq/L = safe; > 1.25 meq/L = unsuitable) [49].

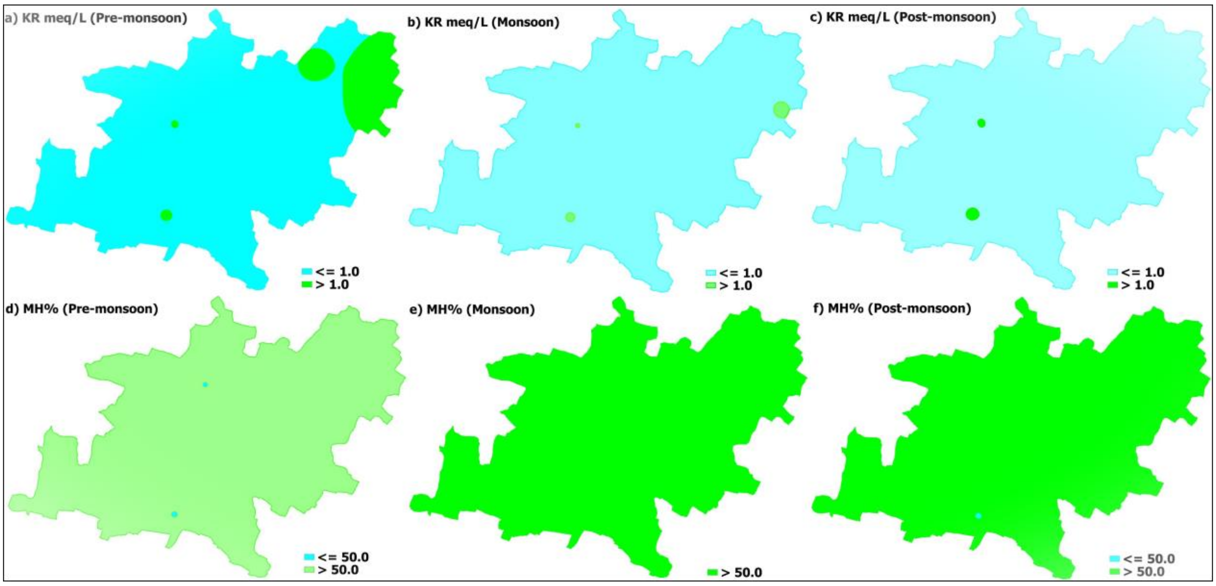

Figure 4. a) KR in pre-monsoon, b) KR in monsoon, c) KR in post-monsoon, d) MH% in pre-monsoon, e) MH% in monsoon, and f) MH% in post-monsoon season

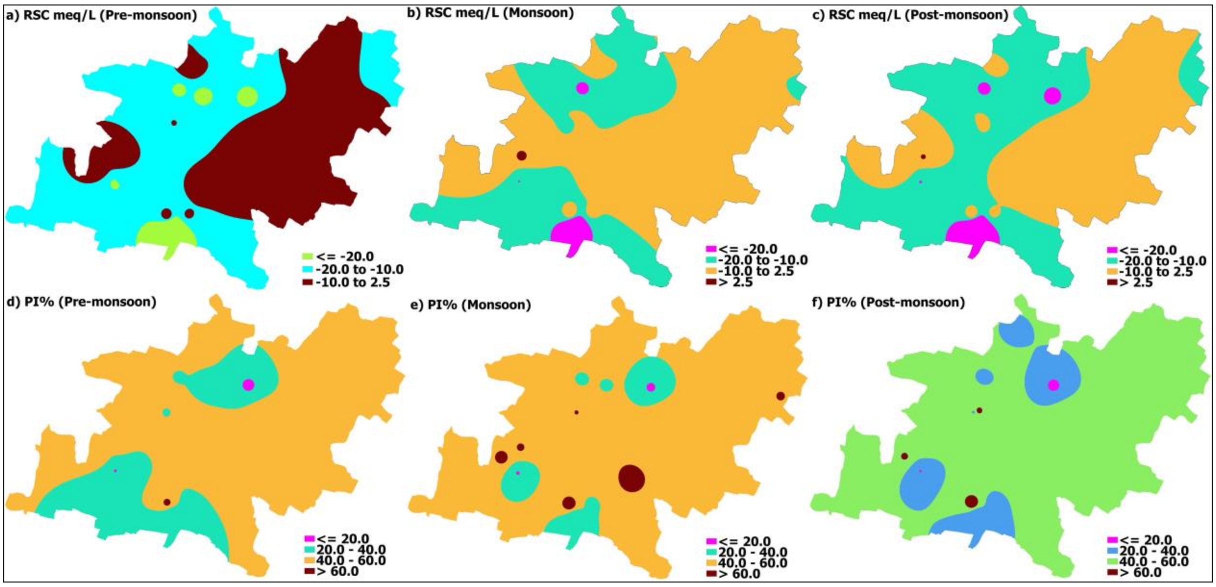

Figure 5. a) RSC in pre-monsoon, b) RSC in monsoon, c) RSC in post-monsoon, d) PI% in pre-monsoon, e) PI% in monsoon, and f) PI% in post-monsoon season

PI: The PI values varied from 16.1 - 65.5 meq/L during the pre-monsoon, 17.2 - 76.0 meq/L during the monsoon, and 16.2 - 77.2 meq/L during the post-monsoon season (Figure 5d - 5f). Based on the values, PI can be divided into three categories [28]: Class I (> 75 % appropriate), Class II (25 - 75 % good), and Class III (< 25 % undesirable). All samples were within Class I, indicating good PI values (Figure 6a).

USSL plot: This plot is a complete tool for determining the suitability of water for irrigation. When the SAR is plotted against EC, the resulting diagram is commonly used to classify irrigation water quality. In the study, approximately 8 % of the water samples were classified as low salinity and medium alkalinity (S1 and C2), 8 % as medium salinity and medium alkalinity (S2 and C2), and 16 % as medium salinity and high alkalinity (S2 and C3). Almost 40 % of the samples were classified as high salinity and alkalinity (S4 and C4) (Figure 6b).

Wilcox diagram: The Wilcox diagram classifies water samples into five categories depending on their Na% and EC. After evaluation, approximately 24 % of the water samples were rated excellent to good, 32 % as good to permissible, 20 % as doubtful to unsuitable, and 24 % as unsuitable for irrigation (Figure 6c).

Piper trilinear plot: The plot visually shows the chemistry of a water sample. It is also helpful to understand the chemical relationships between different ions.

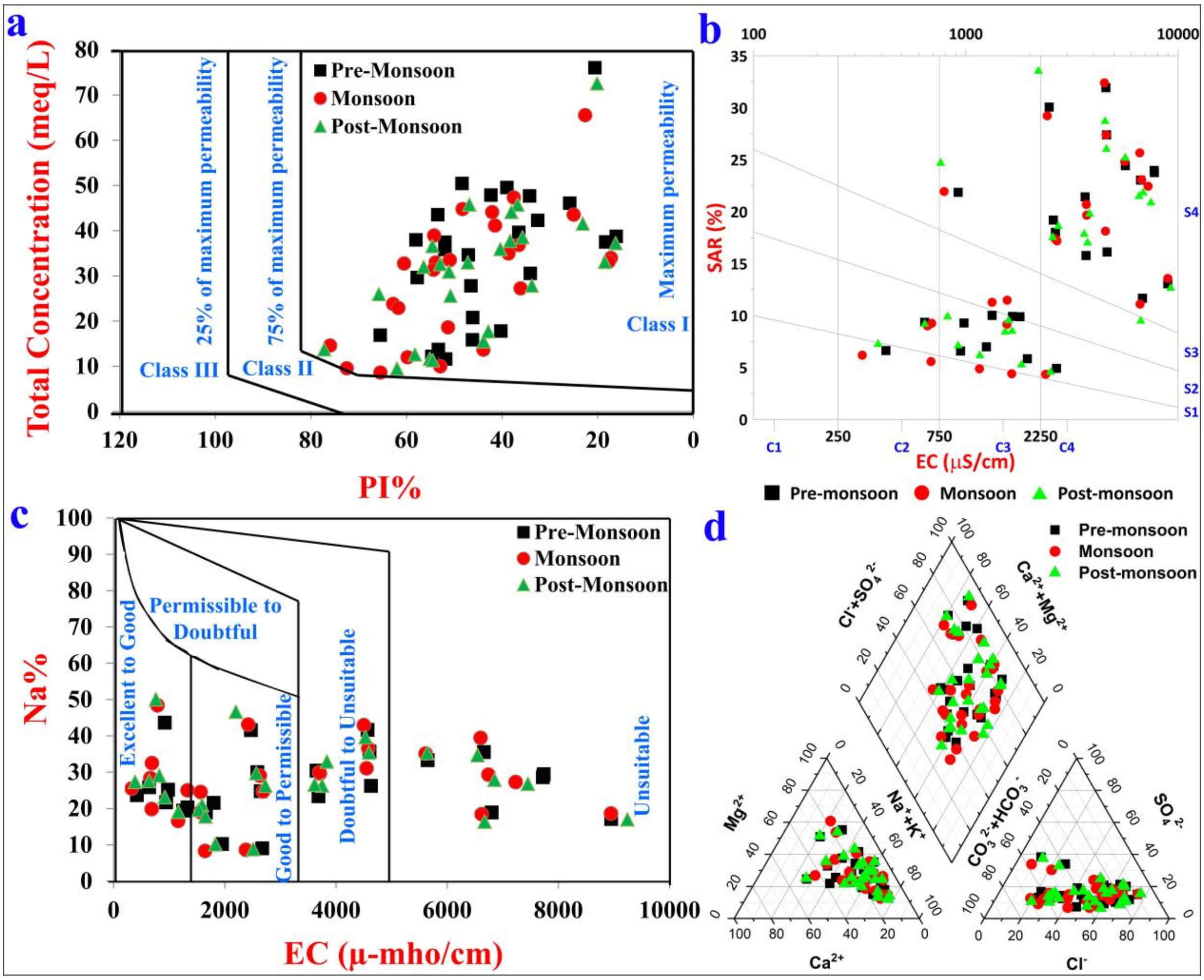

Figure 6: a) PI plot versus total ion concentration, b) USSL plot for water classification, c) Wilcox plot for water classification, and d) Piper trilinear plot for water classification

Four primary types of water have been recognized based on the analysis of the trilinear diagram, which depends on different ionic compositions. During the pre-monsoon, monsoon, and post-monsoon seasons, the dominant water type remains Ca^{2+}-Mg^{2+}-HCO_3^-, as shown by the Piper diagram. In the pre-monsoon season, water chemistry was dominated by Ca^{2+} and Mg^{2+}, with HCO_3^- as the predominant anion, indicating the influence of carbonate rock weathering. During the monsoon season, this pattern remains present, although there is a slight shift towards Na^+ and K^+ in the cation triangle, with some samples showing the appearance of a Ca^{2+}-Mg^{2+}-Cl^- type, probably due to rainwater and runoff. In the post-monsoon season, the Ca^{2+}-Mg^{2+}-HCO_3^- dominance continues, but there is a noticeable presence of Cl^- in some samples, indicating a minor but ongoing influence of the Ca^{2+}-Mg^{2+}-Cl^- type (Figure 6d).

Gibbs plot: Gibbs illustrations are the graphical representations of the ratio of cations [$Na^+/(Na^++Ca^{2+})$] and anions [$Cl^-/(Cl^-+HCO_3^-)$] versus TDS. The plot of [$Na^+/(Na^++Ca^{2+})$] vs. TDS shows that during pre-monsoon, monsoon, and post-monsoon seasons, samples are grouped along the rock dominance line (Figure 7a), with a trend towards evaporation dominance as TDS increases. This suggests that during all seasons, water chemistry is influenced by rock weathering, although evaporation mechanisms become more dominant as TDS increases. The plot of [$Cl^-/(Cl^-+HCO_3^-)$] vs. TDS suggests the increased role of evaporation in water chemistry (Figure 7b).

Except for SAR and MH, a significant difference ($p < 0.05$) in means for all the irrigation indices was observed in different seasons.

Comparison with similar and recent studies

The WQI values from 41.6 - 626.4 in the current study from Jhajjar, Haryana indicates substantial variability in water quality (Table 6). This value is significantly higher than that in Kalanaur (58.3 - 354.5) and Sivas Province, Turkey (30.5 - 81.0). The SAR in Jhajjar is greater than that in Kalanaur (3.2 - 16.4) and Karnal (1 - 19), with a range of 4.3 to 33.7. This indicates that the salinity concerns are more severe. Furthermore, the Na% levels in Jhajjar (8.3 - 50.1 meq/L) are significantly higher than those in Kalanaur (4.2 - 32.7 meq/L) and Kanyakumari (1.1 - 6.7 meq/L), which raises concerns about the contamination of local water sources with Na^+. The RSC values in Jhajjar (- 53.9 - 5.1 meq/L) are in sharp contrast to those reported in other studies, indicating the suitability for irrigation in the region. For example, the RSC range in Inaouene, Morocco (3.6 - 4.5 meq/L) makes the water unsuitable for irrigation. Additionally, the PI in Jhajjar (16.1 - 77.2 meq/L) is higher than that in Kalanaur (15.4 - 59.7 meq/L), indicating its better suitability for irrigation. In general, Jhajjar presents more severe water quality challenges in terms of WQI and MH than other study sites, highlighting the imperative need for effective management and remediation strategies.

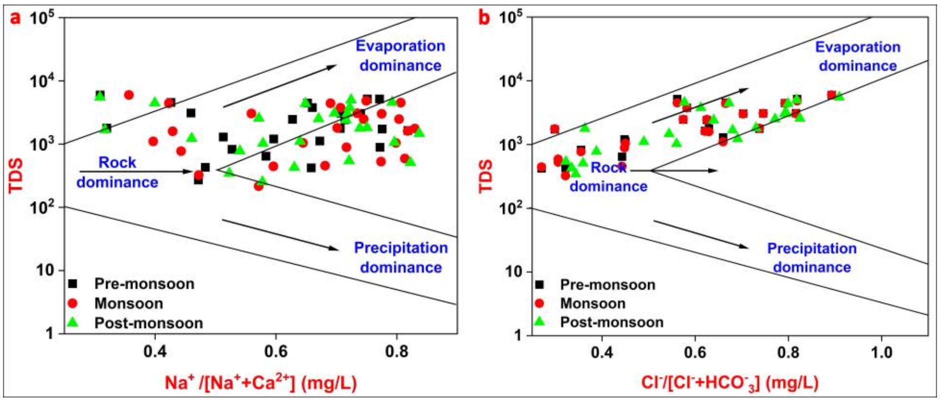

Figure 7. a) Gibbs plot for [$Na^+/(Na^++Ca^{2+})$] vs. TDS and b) [$Cl^-/(Cl^-+HCO_3^-)$] vs. TDS

Table 6. Comparison of results with some similar and recent studies

Study site	WQI	SAR	Na%	RSC	PI	KR	MH	Reference
Jhajjar district (Haryana), India	41.6 - 626.4	4.3 - 33.7	8.3 - 50.1	- 53.9 - 5.1	16.1 - 77.2	0.1 - 1.4	45.5 - 90.1	Present study
Kalanaur block (Rohtak, Haryana), India	58.3 - 354.5	3.2 - 16.4	4.2-32.7	< 1.2	15.4 - 59.7	0.05 - 0.7	44.8 - 93.0	[18]
Karnal district (Haryana), India	-	1 - 19	21.5 - 88.0	0.01 - 7.3	-	-	-	[50]
Sirsa district (Haryana), India	-	3.4 - 9.0	-	- 91.3 - 0.7	55.7 - 89.6	- 0.8 - 2.2	-	[51]
Konkan division (Maharashtra), India	29.9 - 331.0	2.0 - 79.7	-	-	40.9 - 96.9	0.2 - 16.5	-	[52]
Kanyakumari district (Tamil Nadu), India	-	0.2 - 8.4	1.1 - 6.7	- 12.2 - 2.5	28.8 - 96.1	0.09 - 1.9	10.4 - 97.9	[53]
Inaouene (Fes-Taza), Morocco	48.1 - 80.8	10.3 - 69.4	44.0 - 79.2	3.6 - 4.5	50.0 - 81.1	0.8 - 3.7	28.2 - 72.3	[54]
Sivas Province, Turkey	30.5 - 81.0	0.1 - 9.4	3.1 - 57.8	< 1.2	22.1 - 62.9	0.03 - 1.3	-	[55]

* Except for WQI and SAR, values for other indices are expressed in meq/L (the data range shown here corresponds to overall values, not seasonal)

PCA

The calculated factor loadings, eigenvalues, proportion variance (%), and cumulative variance (%) for analysed parameters in different seasons are shown in Table 7. As recommended by the Scree plot, the first three principal components (PCs) for each season with eigenvalues larger than one were selected. These PCs, in each season, accounted for more than 80 % of the cumulative variance. Across all seasons, EC, TDS, Cl^-, and SO_4^{2-} constantly dominate PC1, highlighting their significant influence on water quality variance. In the pre-monsoon season, pH predominantly affects PC2, while turbidity and Mg^{2+} contribute to both PC1 and PC3. Ca^{2+} shows a substantial negative loading on PC2 during the monsoon season, while Na^+ had a negative connection with PC3. During the post-monsoon season, the trends are similar, but Na^+ and K^+ have more significant negative loadings on PC3, while turbidity plays a more significant role in PC3 during the post-monsoon season. In each season, ions with similar loadings on a principal component (PC) correlate positively. For instance, EC, TDS, Cl^-, and SO_4^{2-} all have significant positive loadings on PC1, showing a positive correlation. Na^+ and K^+ ions with negative loadings on PC3 negatively correlate with those with positive loadings on the same component.

HCA

The sampling site clusters change significantly during three seasons, and this method has been previously used for grouping sites [56]. During all three seasons, four significant clusters emerge. In the pre-monsoon season, sites 1, 6, and 17 form a close cluster, with sites 1 and 6 showing considerable resemblance, while sites 25 and 14 group closely within a wider cluster (Figure 8a). During the monsoon season, site 1 joins a cluster of sites 25, 17, and 7, with sites 1 and 25 tightly packed and sites 14 and 15 forming a separate minor cluster (Figure 8b). During post-monsoon season, site 1 clusters with sites 13, 7, and 15, which are highly similar to site 13, while sites 25 and 20 create their own cluster (Figure 8c). Sites 2 and 5 remain consistently clustered across all seasons, but their surrounding group changes: during the pre-monsoon season with sites 8, 24, 11, and 23, during the monsoon season with sites 8, 24, 9, and 18, and during post-monsoon with sites 5, 6, 8, and 24, indicating stable but evolving water quality relationships.

Table 7. PCA loadings for different parameters in various seasons

Parameter	PC1	PC2	PC3	PC1	PC2	PC3	PC1	PC2	PC3
	Pre-monsoon season			Monsoon season			Post-monsoon season		
pH	0.06	0.67	0.45	0.28	0.66	-0.09	-0.01	0.57	0.28
Turbidity (NTU)	0.59	0.29	0.54	0.59	0.12	0.69	0.60	0.10	0.65
TDS (mg/L)	**0.96**	- 0.09	- 0.13	**0.96**	- 0.06	- 0.13	**0.95**	0.04	- 0.11
EC (µS/cm)	**0.95**	- 0.09	- 0.12	**0.96**	- 0.06	- 0.13	**0.96**	- 0.01	- 0.09
Na^+ (mg/L)	0.81	0.15	- 0.46	0.82	0.24	- 0.48	0.78	0.21	- 0.53
K^+ (mg/L)	0.58	0.60	- 0.44	0.58	0.66	- 0.19	0.55	0.64	- 0.37
Ca^{2+} (mg/L)	0.69	-0.58	0.17	0.74	- 0.59	0.02	0.72	- 0.57	0.08
Mg^{2+} (mg/L)	0.74	-0.05	0.47	0.78	- 0.07	0.42	0.77	- 0.15	0.41
Cl^- (mg/L)	**0.93**	-0.20	- 0.08	**0.94**	- 0.19	- 0.04	**0.93**	- 0.11	- 0.14
SO_4^{2-} (mg/L)	**0.89**	-0.10	0.16	**0.88**	- 0.23	0.00	**0.87**	- 0.15	0.13
HCO_3^- (mg/L)	0.26	0.78	- 0.03	0.18	0.75	0.31	0.19	0.81	0.29
Eigenvalue	5.93	1.92	1.21	6.12	1.95	1.05	5.87	1.83	1.23
Proportion variance (%)	53.87	17.48	11.01	55.64	17.72	9.52	53.33	16.67	11.14
Cumulative variance (%)	53.87	71.35	82.36	55.64	73.36	82.88	53.33	70.00	81.14

* Bold values have a significant impact on water chemistry

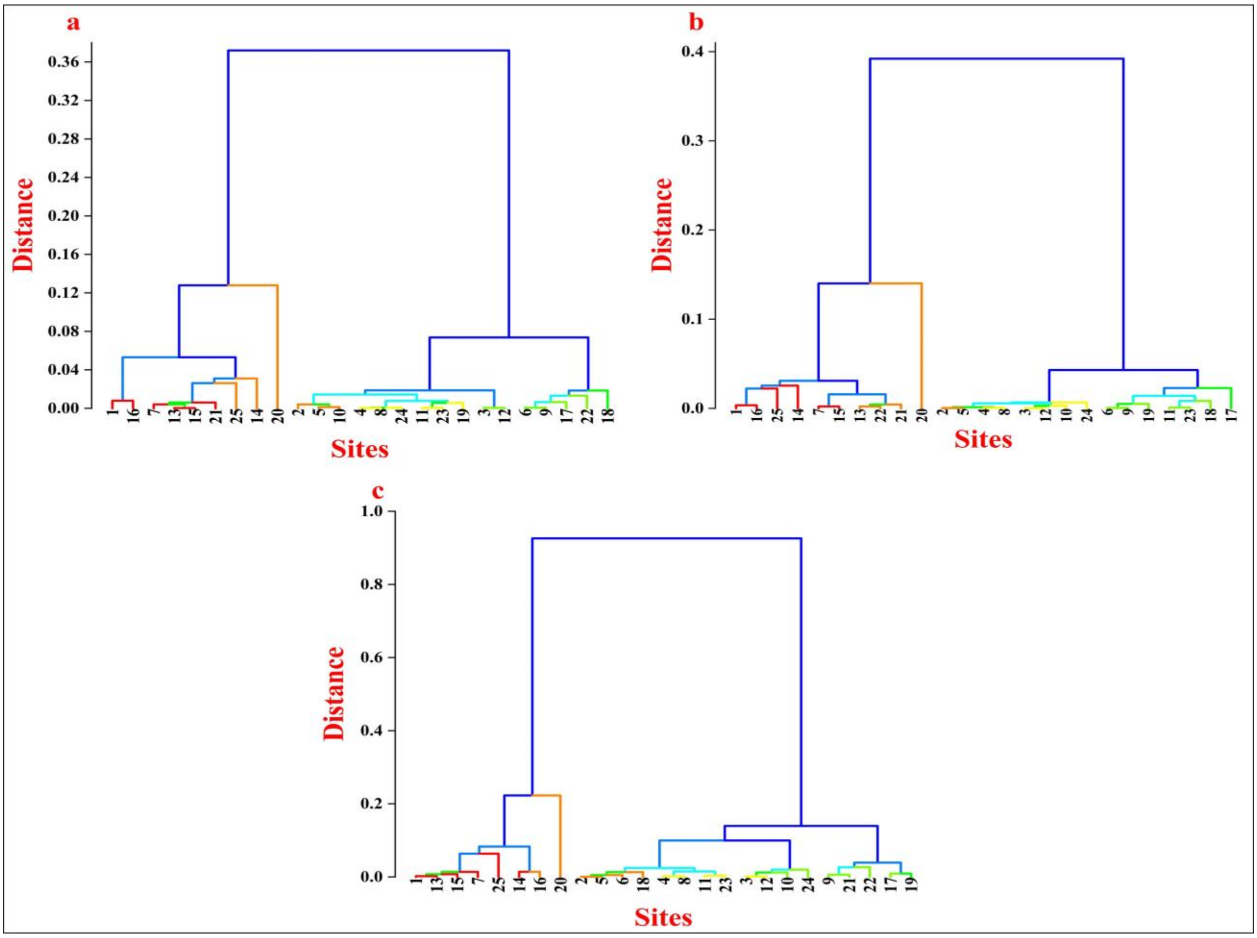

Figure 8. a) HCA plot for pre-monsoon sites, b) HCA plot for monsoon sites, and c) HCA plot for post-monsoon sites

CONCLUSION

This study highlights considerable issues in surface water quality in the wetlands of Jhajjar district, Haryana, especially in light of growing industrial and developmental activities. With most samples unfit for consumption, statistics indicate a significant drop in water quality, affecting public health. The analysis also presents a complex scenario for agriculture. While certain indices suggest that the water is usable for irrigation, the high WQI of most samples, the high MH index, and the USSL diagram indicate potential risks to human health, soil structure, and crop yield, raising concerns about the long-term sustainability of agricultural practices. The Piper trilinear diagram shows the predominance of Ca^{2+}-Mg^{2+}-HCO_3^- in the water chemistry indicating a significant geochemical influence probably caused by prolonged evaporation and rock-water interactions. These findings highlight the complex interplay between natural processes and human influences on water quality. The use of PCA in the study provides a comprehensive understanding of the processes that drive water quality fluctuations, highlighting TDS, EC, and Cl^- as significant parameters affecting water quality. The spatial grouping of sampling sites into major and minor groups shows that localized pollution sources may contribute to overall degradation. Finally, this study highlights the immediate need for focused, location-specific water management plans addressing the quality and sustainability of the local water resources. Without early intervention, the effects could be catastrophic, not only for the environment, but also for the socioeconomic fabric of the community.

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Acknowledgments

For their financial support, the authors thank the University Grants Commission (UGC), New Delhi, the Council of Scientific & Industrial Research (CSIR), New Delhi, the Haryana State Council for Science and Technology (HSCST), SERB-DST, Government of India, New Delhi, and DST-FIST, New Delhi.