Macedonian Journal of Ecology and Environment
Vol. 27, issue 1
pp. 11 - 37
Skopje (2025)
ISSN 1857 - 8330 (on-line)
ISSN 0354-2491 (print)
Original scientific paper
Available online at www.mjee.org.mk
DOI: https://doi.org/10.59194/MJEE2527111k

Geospatial irrigation suitability assessment of groundwater: A case study from Thar desert of India

Leela Kaur[1]*, Prem Godara[1], R. K. Saran[2]

[1] *Department of Environmental Science, Maharaja Ganga Singh University, Bikaner, Rajasthan (INDIA)*

[2] *Government Agriculture College, Gogunda, MPUAT, Udaipur, Rajasthan (INDIA)*

Abstract

The current study assesses the suitability of groundwater for irrigation purpose in an urban area of Northwestern Rajasthan which lies in Thar desert of India. Groundwater samples from tube wells were collected. The irrigation suitability of samples was analyzed by using parameters such as electrical conductivity, total dissolved solids, nitrate, salinity hazard, percentage sodium (% Na), sodium absorption ratio (SAR), residual sodium carbonate (RSC), magnesium absorption ratio (MAR), Kelly's ratio (KR), permeability index (PI), potential salinity (PS), corrosivity ratio (CR), chloro-alkaline indices (CAI-I and CAI-II), Gibb's ratios (GR-I and GR-II), chloride : bicarbonate ratio ($Cl : HCO_3$), magnesium : calcium ratio (Mg : Ca) and sodium : calcium ratio (Na : Ca). Inverse Distance Weighting (IDW) method was used to assess geospatial distribution of irrigation parameters in QGIS software. The results of EC and TDS reveal unsuitability of groundwater for irrigation use as samples fall under C3 and C4 categories. All the samples had less than 60% sodium percentage which is permissible for irrigation purposes. Very high SAR value of more than 26 was not detected. Residual sodium content falls under good category in most samples. However, several samples exhibited magnesium absorption ratio of more than 50 which is unsuitable for irrigation. Kelly's ratios (more than 2) were also found under unsuitable category in 68.75% samples. Potential salinity falls under class III (less than 10) which is injurious and unsatisfactory for irrigation in 70% samples. Corrosivity ratio of less than 1 was observed in 62.5% samples, indicating water is safe for transportation through any type of pipes. Most of the samples had positive chloro-alkali indices CAI-I and CAI-II. Overall, 66.25% samples were detected unsuitable for irrigation chiefly because of highly saline groundwater. The study recommends effective management of groundwater resources particularly for irrigation to ensure sustainable agricultural productivity.

Keywords: Groundwater quality, sustainable agriculture, irrigation, geospatial analysis, Thar desert, salinity hazard

Introduction

India's economy primarily depends on agriculture and more than 60% population is involved in agricultural sector. Agricultural irrigation is vastly done by utilizing groundwater resources. Hence, groundwater quality is a critical factor in ensuring sustainable agricultural practices. The livelihood of Thar desert of Rajasthan is intensely dependent on agriculture. While, agricultural production of Thar desert is dependent on rainfall and groundwater resources. The quality of irrigation water is crucial for sustainable agricultural production. The high-quality irrigation water protects soil health, supports healthy plant growth and maximizes crop yields. Conversely, poor irrigation water quality can hinder plant development, reduce yields, and threaten food security. It can also cause soil salinization, degrading soil fertility and soil productivity. Sustainable agricultural practices, therefore, require diligent

Submitted: 17.03.2025
Accepted: 25.04.2025

* Author for correspondence: leela.kaur@gmail.com

monitoring and management of groundwater quality. By ensuring clean and reliable water sources, farmers can maintain fertile lands and secure long-term agricultural production in desert environments.

Groundwater quality have been investigated to check its suitability for irrigation by several researchers in India (Singh et al. 2020; Karunanidhi et al. 2021; Keesari et al. 2021; Tripathi et al. 2023; Chahal et al. 2023; Bhatnagar & Thakral 2024; Kumar et al. 2024, Sathe et al. 2024; Shaw & Sharma 2024; Singh et al. 2024).

The Thar Desert, also known as the Great Indian Desert, asserts several distinctive features. The Thar Desert have an arid climate. It experiences extreme temperatures, with scorching hot summers and chilly winters. Rainfall is sparse, typically ranging between 100 mm and 500 mm annually. The landscape is dominated by shifting sand dunes, which are continually reshaped by the wind. These dunes can reach impressive heights, creating a unique and ever-changing terrain. Despite its harsh conditions, the Thar Desert supports a variety of plant and animal life. Vegetation is primarily composed of hardy shrubs and grasses, while animals include species such as the Indian gazelle (chinkara), desert fox, and great Indian bustard. The Thar Desert is home to a vibrant cultural heritage, with traditional Rajasthani music, dance, and crafts thriving in the region. The desert is dotted with historic forts, palaces, and temples, reflecting the rich history of its inhabitants. Inhabitants of the Thar Desert primarily engage in agriculture and animal husbandry, adapted to the arid conditions. Crops such as millet, barley, and pulses are commonly grown, and livestock like camels, goats, and sheep are reared. The groundwater quality of Thar Desert is characterized by high presence of fluoride, nitrate, and salinity (Khuhawar et al. 2019; Singh & Bhakar 2021, Begum et al. 2024) putting emphasis on its monitoring and management.

The objective of the current study is to investigate groundwater suitability for irrigation purpose in an urban area of the Thar desert of India.

Methodology

The selected study area is Bikaner city which is situated within the extensive Thar Desert. This vast desert significantly impacts Bikaner's climate, vegetation, and overall lifestyle. The region is characterized by arid conditions, sandy terrain, and extreme temperatures, which collectively shape the unique weather patterns and ecosystem of Bikaner. The sampling locations were carefully selected to provide a representative overview of groundwater quality of the study area. The specific sampling sites are detailed in Table 1.

Samples were collected from 20 groundwater wells of the study area. Samplings were done in pre-monsoon and monsoon seasons for two years (2019 and 2020). Post-monsoon samplings could not be done due to the corona pandemic. Hence, total 80 samples were collected. The filtered water samples were preserved with nitric acid. The selected physicochemical parameters for the study were analysed using standard methods such as electrical conductivity, sodium, potassium, calcium, magnesium, bicarbonate, carbonate, chloride, nitrate and sulphate (APHA 2017). The electrical conductivity (EC) was determined using an electro-conductivity meter. Concentrations of sodium (Na^+) and potassium (K^+) were estimated by flame photometer instrument.

Table 1. Geospatial coordinates of sampling sites of the study area.

Sample number	Sampling site	Latitude N	Longitude E
S1	Raisar	28.05255	73.4779
S2	Naurangdesar	28.0727	73.5455
S3	Sagar	28.0196	73.3906
S4	Ridmalsar	28.0101	73.3762
S5	Gadhwala	27.9221	73.4662
S6	Sinthal	27.9653	73.5991
S7	Napasar	27.9688	73.5558
S8	Udasar	27.5619	73.2647
S9	Naal	28.0306	73.1898
S10	Gajner	27.9364	73.0621
S11	Deshnok	27.7851	73.3446
S12	Palana	27.8470	73.2608
S13	Udairamsar	27.9377	73.3016
S14	Gangasahar	27.9795	73.3082
S15	Patel nagar	28.0024	73.3410
S16	Khara	28.1950	73.3868
S17	Jamsar	28.2521	73.4068
S18	Antyodaya Nagar	28.0221	73.2851
S19	Bichhwal	28.0854	73.3533
S20	Karmisar	28.0020	73.2692

The EDTA titration method was utilized to asses total hardness (TH), calcium (Ca^{2+}), and magnesium (Mg^{2+}). Anions such as carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-), chloride (Cl^-), nitrate (NO_3^-) and sulphate (SO_4^{2-}) were quantified via titration, silver nitrate titration, UV-spectrophotometer and turbidimetric methods respectively.

Irrigation quality indices were assessed to check suitability of groundwater samples for irrigation. The selected irrigation parameters were salinity hazard, percentage sodium (% Na), sodium absorption ratio (SAR), residual sodium carbonate (RSC), magnesium absorption ratio (MAR), Kelly's ratio (KR), permeability index (PI), potential salinity (PS), corrosivity ratio (CR), chloro-alkaline indices (CAI-I and CAI-II), Gibb's ratios (GR-I and GR-II), chloride: bicarbonate ratio (Cl^-: HCO_3^-), magnesium: calcium ratio (Mg^{2+} : Ca^{2+}) and sodium: calcium ratio (Na^+ : Ca^{2+}). These parameters were calculated by the following equations (Sellamuthu et al. 2022):

Percentage Sodium

$$(\%\ Na) = \frac{Na^+}{Na^+ + K^+ + Ca^{2+} + Mg^{2+}} X100$$

Sodium Absorption Ratio

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

Residual Sodium Carbonate

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

Magnesium Absorption Ratio

$$(MAR) = \frac{Mg^{2+}}{(Ca^{2+} + Mg^{2+})} X100$$

Table 2. Classifications of irrigation quality indices.

Parameter	Range of parameter	Class
Electrical conductivity (in µS/cm) (Wilcox 1955)	< 250	Low
	251-750	Medium
	750-2250	High
	2251-6000	Very high
Nitrate (in meq/L) (FAO 1994)	<5	Low
	5-30	Medium
	>30	High
Percentage sodium (%) (Wilcox 1955)	< 60	Permissible
	> 60	Unsuitable
Sodium absorption ratio (in meq/L) (Richards 1954)	0-10	Low
	11-18	Medium
	19–26	High
	> 26	Very high
Residual sodium carbonate (in meq/L) (Eaton 1950)	< 1.25	Safe
	1.25–2.50	Marginally suitable
	> 2.50	Unsuitable
Magnesium absorption ratio (in meq/L) (Raghunath 2007)	< 50	Suitable
	> 50	Unsuitable
Kelly's ratio (in meq/L) (Kelly 1963)	<1	Suitable
	1-2	Marginally suitable
	> 2	Unsuitable
Permeability index (in meq/L) (Doneen 1964)	Class I (> 75%)	Maximum permeability (Suitable)
	Class II (25–75%)	75% permeability (Suitable)
	Class III (< 25%)	25% permeability (Unsuitable)
Potential salinity (in meq/L) (Eaton 1950)	Class I (<5)	Excellent to good
	Class II (5-10)	Good to injurious
	Class III (>10)	Injurious to unsatisfactory
Corrosivity ratio (CR) (Ekbal & Khan 2022)	< 1	Suitable
	> 1	Unsuitable
Chloride: Bicarbonate ratio (Gibbs 1970)	<0.5	Good
	0.5–1.3	Slightly contaminated
	1.3–2.8	Moderately contaminated
	2.8–6.6	Injuriously contaminated
	>6.6	Highly contaminated

Kelly's ratio

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

Permeability index

$$(PI) = \frac{(Na^{+} + K^{+} + \sqrt{HC0_3^{-}}}{(Na^{+} + K^{+} + Ca^{2+} + Mg^{2+})} X100$$

Potential Salinity

$$(PS) = Cl^{-} + 0.5SO_4^{-2}$$

Corrosivity ratio

$$(CR) = \frac{(0.028 * Cl^{-}) + (0.021 * SO_4^{-2})}{0.02 * (HCO_3^{-} + CO_3^{-2})}$$

Chloroalkaline index I

$$(CAI - I) = \frac{(Cl^{-}) - (Na^{+} + K^{+})}{Cl^{-}}$$

Chloroalkaline index II

$$(CAI - II) = \frac{(Cl^{-}) - (Na^{+} + K^{+})}{(SO_4^{-2} + HCO_3^{-} + CO_3^{-2} + NO_3^{-})}$$

Gibb's ratio I

$$(GR - I) = \frac{Cl^{-}}{(Cl^{-} + HCO_3^{-})}$$

Gibb's ratio II

$$(GR - II) = \frac{Na^{+} + K^{+}}{(Na^{+} + K^{+} + Ca^{2+})}$$

The quality of irrigation water is classified based on the irrigation quality indices as shown in Table 2.

The spatial distribution of irrigation groundwater quality parameters was assessed using the Inverse Distance Weighting (IDW) interpolation technique in QGIS 3.38.3 'Grenoble' software.

Results and discussion

Table 3 shows irrigation quality parameters of the study area's ground water in the pre-monsoon season of 2019. All the samples show sodium percentage less than 60 indicating good irrigation quality. Its minimum and maximum values are 22.5 and 45.7 with an average of 36.3. The average sodium absorption ratio (SAR) is 10.37 with a range of 2.95 (Palana) to 21.41 (Udairamsar). The residual sodium carbonate (RSC) is found lowest at Jamsar (-39.6) whereas Ridmalsar have the highest RSC (2.29). The range of magnesium absorption ratio (MAR) is 34.7 (Jamsar) to 80.7 (Patel nagar). Kelly's Ratio (KR) ranges from 0.8 (Jamsar) to 11.6 (Palana). The minimum and maximum values of permeability index (PI) are 16.5 (Udairamsar) and 41.5 (Raisar). Sinthal and Khara sampling sites show potential salinity (PS) as minimum (6.8) and maximum (65.9) in the pre-monsoon season. Palana and Jamsar have corrosivity ratio (CR) of 0.40 and 12.9 as minimum and maximum CR. Chloro-alkaline index (CAI-I and CAI-II) of all the samples have positive values indicating possibility of exchange of Na and K by Mg and Ca. Gibbs ratios i.e., GR-I and GR-II range from 0.606 to 0.951 and from 0.559 to 0.971. Gibbs ratios values for irrigation water is suitable within the range of 0.2 to 0.6 for Gibbs Ratio I and 0.5 to 0.8 for Gibbs Ratio II, indicating a balanced mineral composition that will not be excessively detrimental to plant growth. The ratio of $Cl:HCO_3$ ranges from 1.52 to 19.75. whereas ratios Mg: Ca and Na: Ca have range of 0.53 to 4.19 and 1.26 to 33. Water is classified into 3 categories based on Mg/Ca ratio. These are safe (Mg/Ca ratio less than 1.5), moderate (Mg/Ca ratio 1.5 to 3), and unsafe (Mg/Ca ratio more than 3) water class. It was found that S5 falls under unsafe class as per Mg/Ca ratio.

Table 4 depicts irrigation quality parameters of monsoon season of 2019. Sodium percentage in all the samples lies under good category with values less than 60 %. The maximum and minimum values of SAR are found in Napasar (2.64) and Palana (17.99). The lowest and the highest RSC are found at Jamsar (-37.3) and Ridmalsar (1.99). The range of MAR is 41.7 (Jamsar) to 78.2 (Patel nagar). Jamsar and Palana show KR values of 0.9 and 7.8. The minimum and maximum values of PI are found in Udairamsar (17.8) and Jamsar (40.2). Sinthal and Khara sampling sites show potential salinity (PS) as minimum (7.12) and maximum (67.08). The minimum and maximum CR is observed in Palana (0.45) and Jamsar (6.93). The CAI-I and CAI-II of all the samples are positive values. The GR-I and GR-II have range of 0.55-0.94 and 0.60-0.95. The ratio of $Cl:HCO_3$ ranges from 1.26 to 16.73 and other ratios Mg: Ca and Na: Ca have range of 0.71 to 3.59 and 1.54 to 21.74.

Irrigation quality parameters of pre-monsoon and monsoon seasons of 2020 groundwater of the study area's groundwater are presented in Table 5 and 6 respectively. The range of percentage Na in pre-monsoon and monsoon seasons is 21.6 to 40.3 and 26.2 to 44.5. SAR values range from 2.35 to 12.46 (pre-monsoon) and 2.93 to 18.14 (monsoon) in 2020. The range of RSC in pre-monsoon and monsoon is -19.28 to 1.62 and -6.92 to 6.07. MAR range from 28 to 59.2 (pre-monsoon) and 40.3 to 76.2 (monsoon). The pre-monsoon and monsoon seasons KR values are 0.77 to 4.33 and 1.12 to 8.53. Permeability index of pre-monsoon and monsoon is observed as 17.2 to 37.8 and 19.4 to 38.2. Potential salinity varies from 4.99 to 32.08 (pre-monsoon) and 2.49 to 37.93 (monsoon). While, corrosivity ratio fluctuates from 0.53 to 3.60 (pre-monsoon) and 0.10 to 4.86 (monsoon). Most samples have positive values of CAI-I and CAI-II. However, CAI-I ratio with negative values is seen in two sampling sites of pre-monsoon [Gajner (-3.1), and Palana (-0.1)] and two sampling sites of monsoon [Palana (-7.8) and Gangasahar (-3.3)]. Whereas, the negative values of CAI-II are found in two sampling sites of monsoon i.e., Palana (-2.4) and Gangasahar (-0.7). The GR-I and GR-II have range of 0.40-0.93 and 0.609-0.910 in pre-monsoon. Though, GR-I and GR-II values in monsoon are 0.486 to 0.942 and 0.719 to 0.946. In the pre-monsoon, $Cl: HCO_3$ ratio ranges from 0.7 to 13.7 and other ratios Mg: Ca and Na: Ca range from 0.4 to 1.5 and 1.5 to 10. The $Cl: HCO_3$ ratio ranges from

Table 3. Irrigation quality parameters of pre-monsoon 2019 groundwater of the study area.

Sample No.	% Na	SAR	RSC	MAR	KR	PI	PS	CR	CAI-I	CAI-II	GR-I	GR-II	Cl: HCO_3	Mg: Ca	Na: Ca
S1	38.3	13.3	-8.3	55.2	3.3	41.5	36.5	2.2	33.5	29.5	1.0	0.9	19.75	1.23	7.44
S2	42.8	14.9	1.2	54.7	6.1	33.5	22.4	1.2	19.6	17.8	0.8	0.9	4.87	1.21	13.37
S3	42.8	15.4	1.7	66.9	6.1	33.0	18.1	1.0	15.1	14.3	0.8	0.9	3.73	2.02	18.48
S4	42.6	15.0	2.3	65.5	6.0	32.8	8.9	0.7	3.9	4.7	0.6	0.9	1.54	1.90	17.39
S5	29.1	4.0	-1.4	63.1	1.4	18.9	8.0	0.5	6.2	6.0	0.8	0.8	3.33	1.71	3.82
S6	39.6	8.1	0.4	52.9	4.0	21.8	6.8	0.6	4.2	5.0	0.7	0.9	2.95	1.12	8.57
S7	32.4	3.7	0.6	70.4	1.9	24.1	11.9	0.6	11.2	10.6	0.9	0.9	6.19	2.38	6.52
S8	39.9	10.7	-1.6	58.6	4.1	25.8	19.1	1.1	17.1	15.0	0.9	0.9	8.66	1.42	9.89
S9	38.6	10.0	-2.2	71.0	3.5	24.9	23.7	3.5	18.5	18.2	0.9	0.9	8.29	2.44	12.17
S10	40.4	12.1	-2.2	65.9	4.3	28.3	43.6	3.4	39.7	38.3	0.9	0.9	18.62	1.93	12.61
S11	42.9	15.4	-2.0	66.3	6.2	29.7	10.6	1.3	6.9	4.0	0.9	0.9	6.96	1.96	18.32
S12	45.7	21.4	0.4	64.9	11.6	31.8	9.8	0.4	6.8	1.1	0.8	1.0	4.80	1.85	33.01
S13	24.3	2.9	-4.5	52.1	1.0	16.5	7.4	1.7	4.4	4.6	0.8	0.7	3.21	1.09	2.02
S14	34.0	6.8	-0.3	72.3	2.2	23.6	31.1	1.3	29.4	28.5	0.9	0.9	7.59	2.61	7.81
S15	29.9	8.2	-12.6	80.7	1.5	31.0	19.0	0.8	16.9	15.7	0.8	0.9	5.08	4.19	7.80
S16	26.8	7.1	-24.5	49.1	1.2	35.9	65.9	4.9	59.5	57.9	0.9	0.7	18.67	0.97	2.28
S17	22.5	5.9	-39.6	34.7	0.8	37.5	60.8	12.9	42.6	42.5	0.9	0.6	15.47	0.53	1.26
S18	42.4	12.4	1.9	64.5	5.8	27.1	19.2	0.9	17.4	16.3	0.8	0.9	5.09	1.82	16.36
S19	37.4	10.4	-5.2	62.5	3.0	28.9	22.9	2.0	20.0	17.4	0.9	0.9	10.56	1.67	8.12
S20	35.2	9.4	-5.7	62.5	2.4	30.6	17.9	0.9	15.4	14.0	0.8	0.9	4.91	1.67	6.47

Table 4. Irrigation quality parameters of monsoon 2019 groundwater of the study area.

Sample No.	% Na	SAR	RSC	MAR	KR	PI	PS	CR	CAI-I	CAI-II	GR-I	GR-II	Cl: HCO_3	Mg: Ca	Na: Ca
S1	34.9	10.4	-10.0	56.4	2.4	35.9	33.8	2.2	30.5	28.1	0.9	0.8	16.73	1.29	5.43
S2	41.2	13.2	0.9	55.7	5.0	32.0	22.8	1.2	19.9	18.4	0.8	0.9	5.37	1.26	11.21
S3	40.3	12.8	0.3	65.6	4.2	32.9	19.0	1.0	16.0	15.2	0.8	0.9	3.58	1.90	12.32
S4	40.8	14.0	2.0	64.1	4.8	35.2	8.9	0.7	3.0	4.7	0.6	0.9	1.26	1.79	13.25
S5	30.4	5.2	-0.7	59.8	1.8	21.3	9.6	0.6	7.4	7.3	0.7	0.8	2.96	1.49	4.44
S6	40.3	9.3	1.3	49.4	4.8	23.7	7.1	0.6	4.1	5.0	0.7	0.9	2.39	0.98	9.45
S7	24.9	2.6	-0.5	67.6	1.1	21.2	13.4	0.7	12.6	12.1	0.9	0.8	6.81	2.08	3.44
S8	38.2	10.1	-4.5	55.0	3.3	25.9	17.3	1.2	15.3	11.5	0.9	0.9	15.84	1.22	7.39
S9	39.0	9.9	-0.7	53.1	3.7	26.3	22.9	2.6	17.1	17.1	0.9	0.9	6.60	1.13	7.83
S10	39.0	10.8	-1.8	65.9	3.7	26.9	37.4	3.0	33.2	32.4	0.9	0.9	14.52	1.93	10.98
S11	42.3	14.4	-1.9	56.5	6.0	29.4	13.2	1.3	10.0	7.5	0.9	0.9	7.86	1.30	13.77
S12	43.8	18.0	-0.4	64.2	7.8	33.3	9.9	0.5	6.6	3.2	0.8	1.0	4.19	1.79	21.74
S13	26.7	3.7	-3.4	56.1	1.2	17.8	11.4	1.4	9.0	8.7	0.8	0.7	5.01	1.28	2.80
S14	33.4	6.7	0.6	66.3	2.1	24.6	42.3	1.8	39.6	38.9	0.9	0.9	8.71	1.97	6.32
S15	32.6	9.8	-9.5	78.2	2.0	34.9	22.1	1.0	19.7	18.0	0.8	0.9	4.96	3.59	9.10
S16	25.5	6.8	-25.7	49.2	1.1	36.6	67.1	4.0	61.4	59.9	0.9	0.7	15.62	0.97	2.10
S17	23.6	6.6	-37.3	41.7	0.9	40.2	48.4	6.9	34.1	34.0	0.9	0.6	13.26	0.71	1.54
S18	39.9	10.6	-1.0	54.8	4.1	27.1	23.8	1.3	21.6	19.9	0.9	0.9	7.64	1.21	9.09
S19	38.2	11.4	-4.2	58.9	3.4	31.7	20.2	1.6	16.8	14.9	0.9	0.9	7.98	1.44	8.29
S20	35.5	9.5	-5.6	57.9	2.6	29.5	24.7	2.0	21.0	19.9	0.9	0.9	9.50	1.38	6.14

Table 5. Irrigation quality parameters of pre-monsoon 2020 groundwater of the study area.

Sample No.	% Na	SAR	RSC	MAR	KR	PI	PS	CR	CAI-I	CAI-II	GR-I	GR-II	Cl: HCO_3	Mg: Ca	Na: Ca
S1	37.8	12.0	-7.1	49.6	3.2	37.8	30.3	2.8	25.2	23.6	0.9	0.9	13.72	0.98	6.28
S2	35.0	9.4	-6.6	47.6	2.4	32.9	24.8	2.0	19.8	18.9	0.9	0.8	6.71	0.91	4.52
S3	36.0	9.6	-3.7	57.8	2.7	30.2	20.2	1.5	16.0	15.6	0.8	0.9	5.22	1.37	6.29
S4	39.6	12.5	-2.2	54.8	3.9	33.7	9.6	1.3	2.9	4.8	0.7	0.9	2.31	1.21	8.70
S5	21.6	2.3	-1.4	54.2	0.8	18.9	9.5	0.5	8.1	8.0	0.8	0.6	3.25	1.18	1.68
S6	23.0	2.7	-3.8	50.2	0.9	17.2	23.3	2.2	20.0	19.6	0.9	0.6	8.97	1.01	1.72
S7	22.6	2.7	-2.8	59.2	0.8	18.5	24.7	2.0	21.3	21.0	0.9	0.7	7.56	1.45	2.05
S8	30.3	6.0	-7.0	49.4	1.6	22.4	11.1	1.0	8.0	7.3	0.8	0.8	4.75	0.97	3.17
S9	39.9	11.0	1.6	57.4	4.2	29.4	21.1	1.5	17.0	16.7	0.8	0.9	3.82	1.35	9.81
S10	40.3	10.7	1.6	56.8	4.3	28.3	5.6	1.0	-3.1	1.5	0.4	0.9	0.68	1.32	10.02
S11	25.8	4.5	-4.4	55.3	1.1	22.7	14.1	0.8	11.0	11.1	0.7	0.7	2.23	1.24	2.40
S12	25.6	3.8	-4.3	55.2	1.1	18.3	5.0	0.9	-0.1	2.1	0.5	0.7	1.21	1.23	2.36
S13	32.7	5.7	-4.4	43.5	1.9	20.0	6.9	1.0	3.6	3.4	0.8	0.8	3.34	0.77	3.41
S14	38.3	10.5	-1.4	47.8	3.3	31.6	28.4	1.8	24.2	23.2	0.9	0.9	6.35	0.92	6.37
S15	31.9	6.3	-4.8	45.5	1.8	24.0	17.4	1.4	14.1	13.5	0.8	0.8	4.73	0.83	3.29
S16	32.0	8.2	-12.3	39.3	1.8	33.1	32.1	3.6	25.8	24.9	0.9	0.8	11.90	0.65	3.00
S17	26.2	6.0	-19.3	28.0	1.1	31.7	24.7	2.4	18.3	18.1	0.8	0.6	5.44	0.39	1.55
S18	36.7	9.4	-5.0	46.0	2.9	28.8	18.7	2.3	14.2	13.4	0.9	0.8	6.97	0.85	5.31
S19	33.7	8.4	-8.8	47.0	2.2	29.5	25.6	2.9	21.2	19.8	0.9	0.8	11.00	0.89	4.07
S20	38.7	8.4	-1.4	47.1	3.6	22.0	11.2	1.7	7.6	7.2	0.8	0.9	5.56	0.89	6.76

Table 6. Irrigation quality parameters of monsoon 2020 groundwater of the study area.

Sample No.	% Na	SAR	RSC	MAR	KR	PI	PS	CR	CAI-I	CAI-II	GR-I	GR-II	Cl: HCO_3	Mg: Ca	Na: Ca
S1	43.7	18.1	0.5	54.9	7.2	37.7	37.5	1.5	35.5	32.4	0.9	0.9	12.33	1.22	16.08
S2	38.4	11.8	-5.8	52.3	3.4	34.0	26.8	2.0	23.7	20.9	0.9	0.9	12.66	1.10	7.12
S3	37.5	10.5	-4.1	53.1	3.1	31.1	17.6	0.9	15.2	12.9	0.9	0.9	7.01	1.13	6.55
S4	39.9	11.8	-0.3	53.3	4.1	31.8	18.8	1.0	15.9	14.6	0.8	0.9	3.92	1.14	8.73
S5	26.2	3.5	-1.8	56.2	1.1	19.4	6.1	0.4	4.0	4.3	0.6	0.7	1.85	1.28	2.55
S6	29.4	2.9	6.1	40.3	1.5	35.1	20.4	0.7	19.3	19.2	0.8	0.7	3.45	0.68	2.49
S7	35.5	6.1	1.2	52.3	2.5	21.9	14.8	0.5	13.7	13.0	0.8	0.8	5.26	1.10	5.32
S8	38.7	8.4	-0.4	44.9	3.7	22.6	5.6	0.7	1.6	2.2	0.7	0.9	2.29	0.81	6.79
S9	39.8	10.2	-1.5	47.3	4.0	26.0	22.8	1.4	20.5	18.5	0.9	0.9	9.49	0.90	7.61
S10	42.4	10.5	2.6	41.7	6.1	24.1	22.0	1.1	20.0	18.9	0.9	0.9	8.08	0.71	10.37
S11	39.3	10.0	3.5	52.9	3.8	29.2	12.8	0.6	9.9	10.0	0.7	0.9	2.09	1.12	8.02
S12	41.3	12.6	-0.7	44.5	5.0	30.2	2.5	0.1	-7.8	-2.4	0.5	0.9	0.95	0.80	9.07
S13	34.0	6.7	-3.4	51.0	2.2	22.1	20.0	1.7	17.3	16.2	0.9	0.8	7.86	1.04	4.59
S14	39.8	10.4	-2.6	42.9	4.0	26.4	4.5	1.0	-3.3	-0.7	0.6	0.9	1.83	0.75	7.07
S15	41.8	15.2	0.0	47.3	5.3	38.2	13.2	0.8	9.0	8.4	0.7	0.9	2.96	0.90	10.13
S16	42.7	15.7	-1.8	55.9	6.1	33.5	9.3	0.6	5.5	2.0	0.8	0.9	4.35	1.27	13.87
S17	44.5	17.0	2.0	50.8	8.5	31.0	19.7	0.7	18.0	15.3	0.9	0.9	7.59	1.03	17.36
S18	37.1	9.6	-2.0	45.7	3.0	30.3	9.8	0.9	4.7	5.5	0.7	0.8	1.96	0.84	5.48
S19	33.1	8.3	-6.9	76.2	2.0	26.2	24.1	1.6	21.3	19.6	0.9	0.9	10.16	3.20	8.39
S20	34.3	6.6	-3.8	41.8	2.2	21.8	37.9	4.9	31.8	31.3	0.9	0.8	16.14	0.72	3.85

0.9 to 16.1 and other ratios Mg: Ca and Na: Ca range from 0.68 to 3.2 and 2.5 to 17.4 in the monsoon season.

Overall, electrical conductivity of high salinity (751 to 2250 µS/cm) and very high salinity (more than 2250 µS/cm) are found in the ground water. High salinity is shown by 5 and 8 samples of monsoon and pre-monsoon season of 2020. 7 samples of each monsoon and pre-monsoon of 2019 exhibit high salinity too. Very high salinity is shown by 15 samples of monsoon and 12 samples of pre-monsoon season of 2020. Samples of 2019 have very high salinity. High nitrate concentration (more than 30 mg/L) is found in 29 pre-monsoon samples and 34 monsoon samples. Whereas, medium nitrate concentration of more than 5 to 30 mg/L is observed in 11 pre-monsoon samples and 06 monsoon samples. Low nitrate concentration (less than 5 mg/L) is not detected in any sample. All the samples have permissible percentage sodium content (less than 60%). Most of the samples have low SAR values (0-10) i.e., 25 samples of pre-monsoon and 19 samples of monsoon season. Medium SAR category (more than 10 to 18) is found in 14 samples of pre-monsoon and 20 samples of monsoon. High SAR category (more than 18 to 26) is found in one sample of pre-monsoon as well as one sample of monsoon. Very high SAR category (more than 26) is not detected in any sample. Good category of residual sodium content (<1.25) is seen in the most samples (33 samples of pre-monsoon and 35 samples of monsoon) except 7 samples of pre-monsoon and 2 samples of monsoon falls under marginally suitable category of RSC (1.25-2.50). Monsoon season's three samples show more than 2.50 RSC which is unsuitable for irrigation. Permissible MAR (less than 50) is observed in 13 samples of pre-monsoon and 12 samples of monsoon. However, 27 samples of pre-monsoon and 28 samples of monsoon falls under unsuitable category of MAR (more than 50). Similarly, unsuitable category of KR (more than 2) is found in most samples (24 samples of pre-monsoon and 31 samples of monsoon). However, marginally suitable category of KR (1 to 2) is seen in 12 samples of pre-monsoon and 08 samples of monsoon.

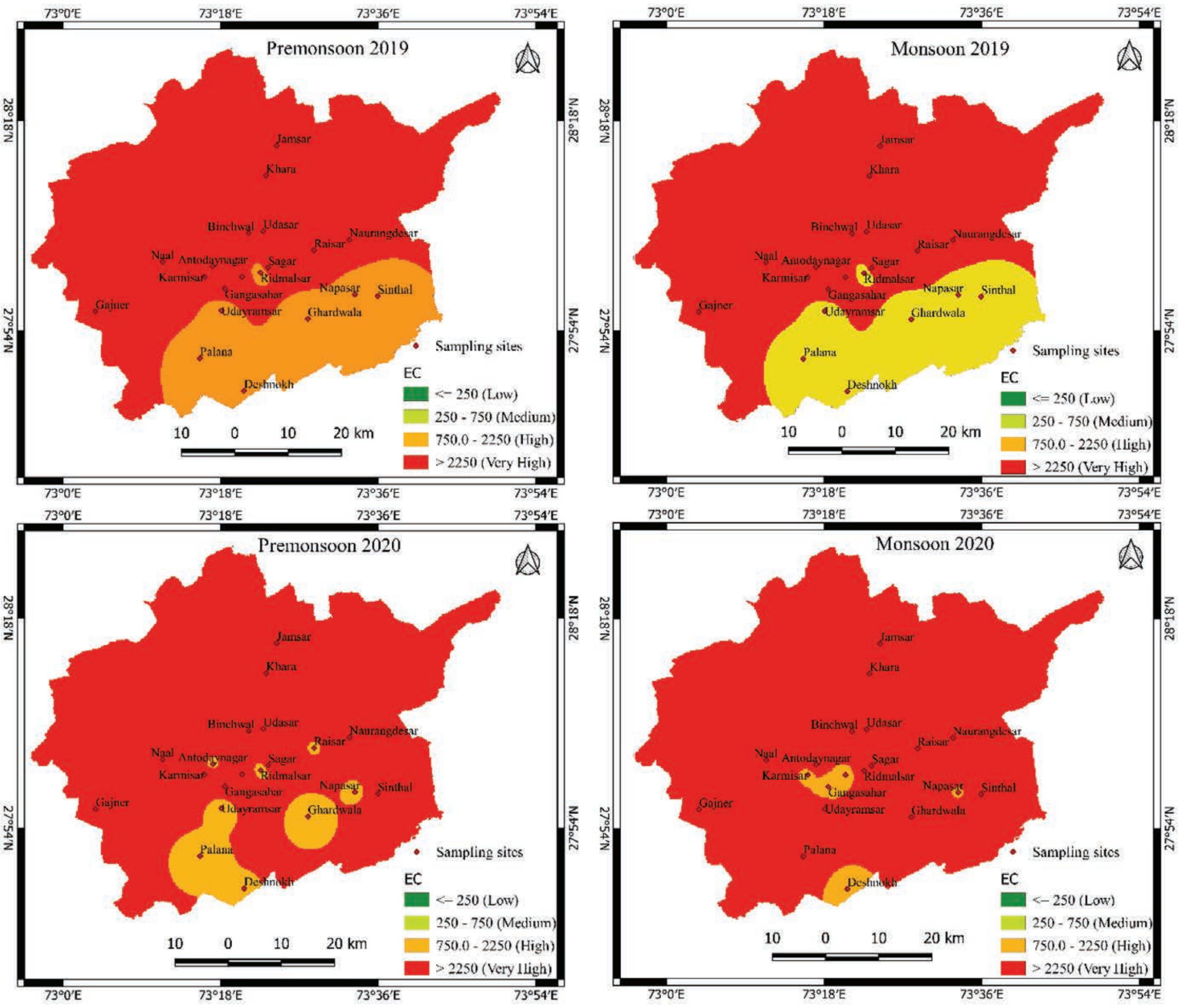


Figure 1. Spatial distribution of electrical conductivity (EC) for irrigation quality in pre-monsoon and monsoon seasons of 2019 and 2020.

Only 1 sample of monsoon and 4 samples of pre-monsoon fall under suitable category of KR (less than 1). Maximum permeability (Class I) of more than 75 PI is not assessed in any sample. Class II of PI with 25 to 75 % permeability is seen in 25 samples of pre-monsoon and 29 samples of monsoon. Class III of PI with less than 25 % permeability is found in 15 samples of pre-monsoon and 11 samples of monsoon. Potential salinity (PS) of most samples falls under class III (less than 10) which is injurious and unsatisfactory for irrigation (30 samples of each pre-monsoon and monsoon seasons). Class II of PS (5 to 10) is seen in 10 samples of pre-monsoon and 08 samples of monsoon which is good to injurious for irrigation. Only 2 samples of monsoon season display class I (less than 5) of PS which is excellent to good characteristics. Corrosivity ratio of less than 1 is observed in most samples (27 samples of pre-monsoon and 23 samples of monsoon) indicating that water is safe for transportation through any type of pipes. Although, CR more than 1 indicates that water is unsuitable for transportation through the metallic pipe and it can only be transported through PVC pipes. The value of CR more than 1 is seen in 13 samples of pre-monsoon and 17 samples of monsoon. Most samples have positive CAI-I except 2 samples of each pre-monsoon and monsoon. Positive values of CAI-II are also seen in utmost samples with exception of 2 samples of monsoon. Most samples show Cl: HCO_3 ratio of more than 6.6 which is highly contaminated class.

The spatial variations of irrigation quality indices of groundwater samples of the study area are illustrated in Figures 1 to 13. The spatial distribution of electrical conductivity (EC) in pre-monsoon and monsoon seasons of 2019 and 2020 is displayed in Figure 1. In the pre-monsoon season, the high EC values (750-2250 µS/cm) are mainly found in the central regions, with some pockets exhibiting very high EC values (>2250 µS/cm). These areas might face salinity issues, affecting crop yield. EC values tend to decrease during the monsoon season due to rainfall dilution, but some regions still exhibit high to very high EC levels, indicating localized

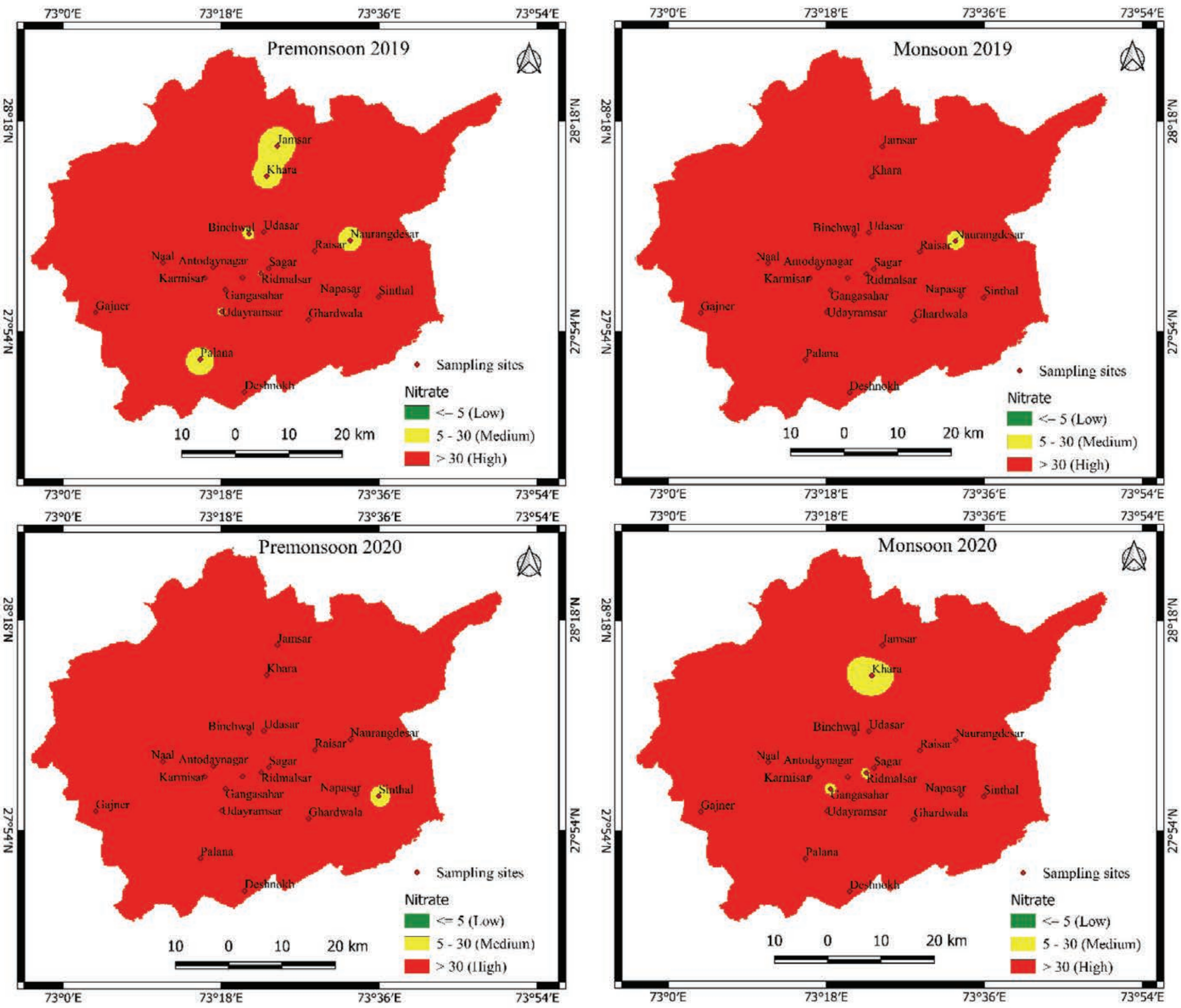


Figure 2. Spatial distribution of nitrate (NO_3) for irrigation quality in pre-monsoon and monsoon seasons of 2019 and 2020.

and persistent salinity problems. The maps clearly show seasonal variations in electrical conductivity.

The spatial distribution of nitrate (NO_3) in pre-monsoon and monsoon seasons of 2019 and 2020 is exhibited in Figure 2. In the pre-monsoon season, most areas have low nitrate concentrations (<5 mg/L), with sporadic medium levels (5-30 mg/L) and rare high concentrations (>30 mg/L). This suggests limited nitrate pollution before the monsoon. Nitrate levels increase during the monsoon, especially in areas likely affected by agricultural runoff. This increase can be attributed to fertilizer leaching into groundwater during rainfall. The rise in nitrate levels during the monsoon highlights the impact of agricultural practices on water quality. Hence, proper management of fertilizer application and runoff is crucial to maintain safe nitrate levels.

The spatial distribution of percentage sodium (Na%) in pre-monsoon and monsoon seasons of 2019 and 2020 is exhibited in Figure 3. Sodium percentages are generally within permissible limits (<60%) across most areas in pre-monsoon season. Some regions exceed this threshold, indicating potential sodicity problems. While, sodium percentage values remain relatively stable, with some areas showing a slight increase during the monsoon. This could be due to the mobilization of sodium ions with increased water flow. High sodium levels are more localized and persistent, indicating specific areas that may require targeted interventions for salinity and sodicity management.

The spatial distribution of sodium absorption ratio (SAR) of pre-monsoon (2019 and 2020) season maps (Figure 4) show that the SAR values are generally higher in the southern and western parts of the study area. The SAR values range from less than 10 to greater than 26. Elevated SAR values indicate that groundwater in these areas has a higher sodium concentration relative to calcium and magnesium, which can affect soil structure and permeability. High SAR can lead to soil dispersion, reduced infiltration, and poor crop yields. Areas with SAR values greater than 26 are particularly concerning

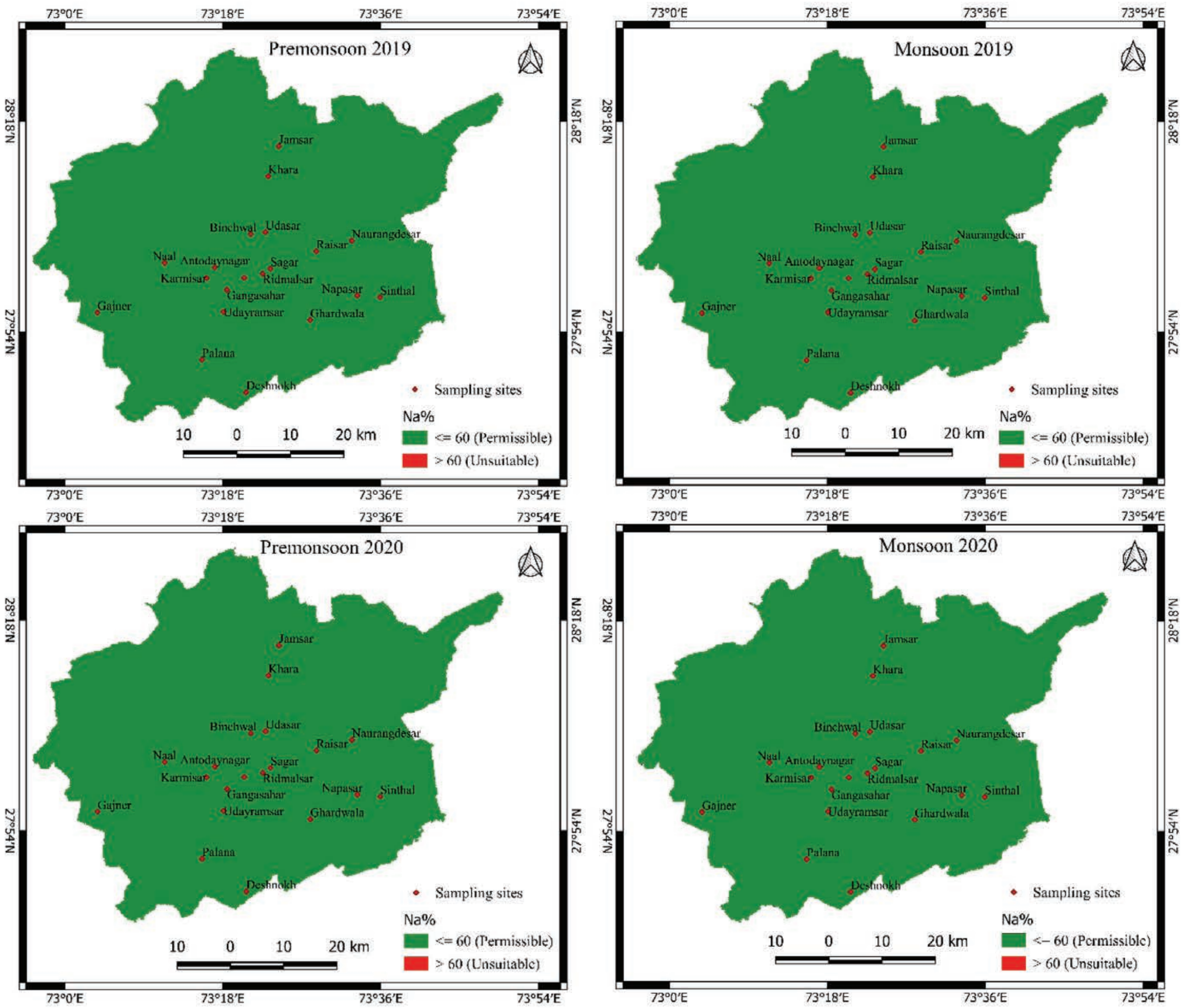


Figure 3. Spatial distribution of percentage sodium for irrigation quality in pre-monsoon and monsoon seasons of 2019 and 2020.

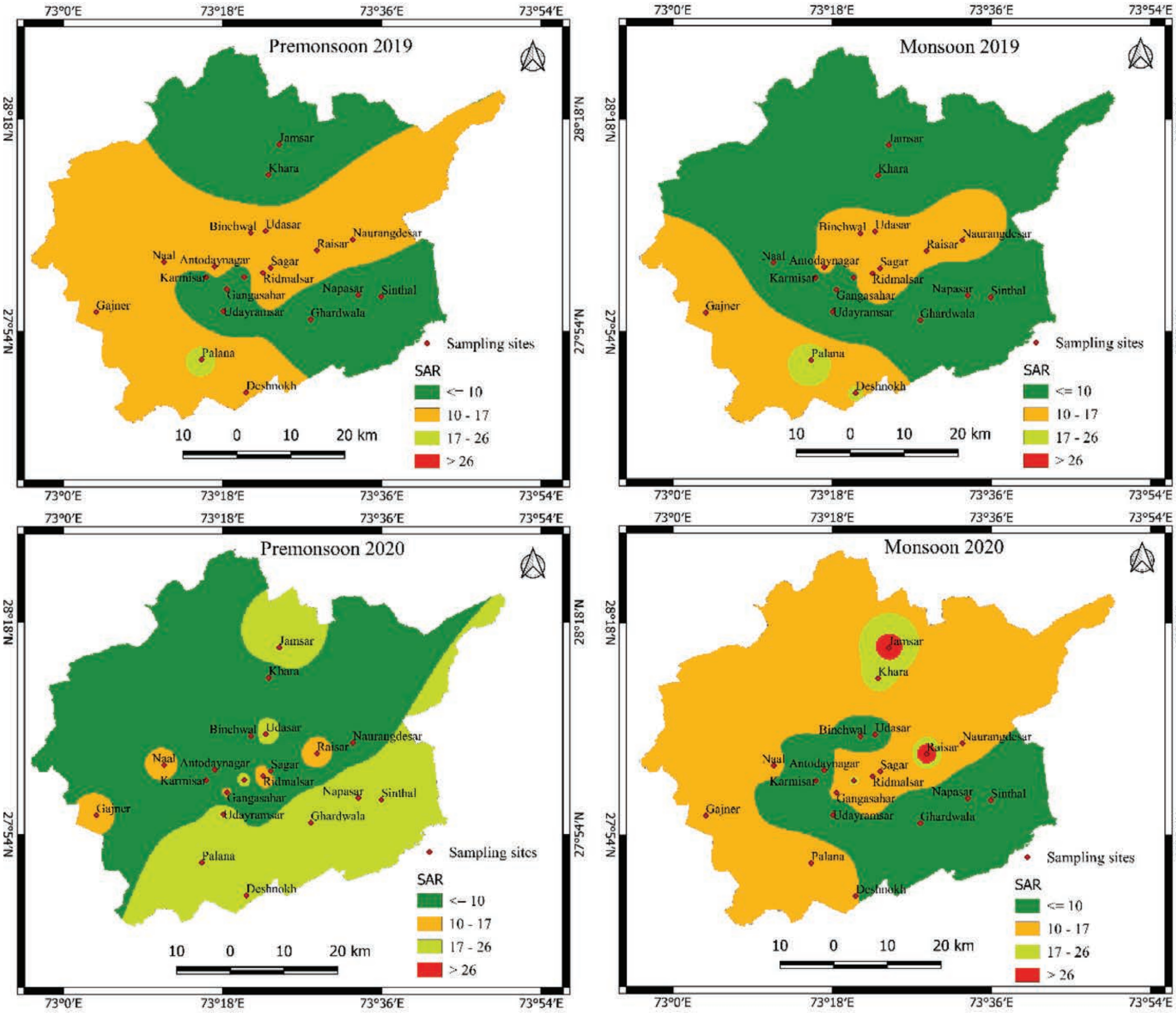


Figure 4. Spatial distribution of sodium absorption ratio (SAR) for irrigation quality in pre-monsoon and monsoon seasons of 2019 and 2020.

for irrigation purposes. The spatial distribution maps of monsoon (2019 and 2020) season depict that SAR values decrease slightly, with most areas still showing high values, but with some reduction in the range. The monsoon rainfall likely dilutes sodium concentrations, temporarily reducing SAR values. However, the persistent high SAR values suggest that natural and anthropogenic sources of sodium remain significant.

Spatial distribution of residual sodium carbonate (RSC) for irrigation quality in pre-monsoon and monsoon seasons of 2019 and 2020 is illustrated in Figure 5. RSC values greater than 2.50 (unsuitable for

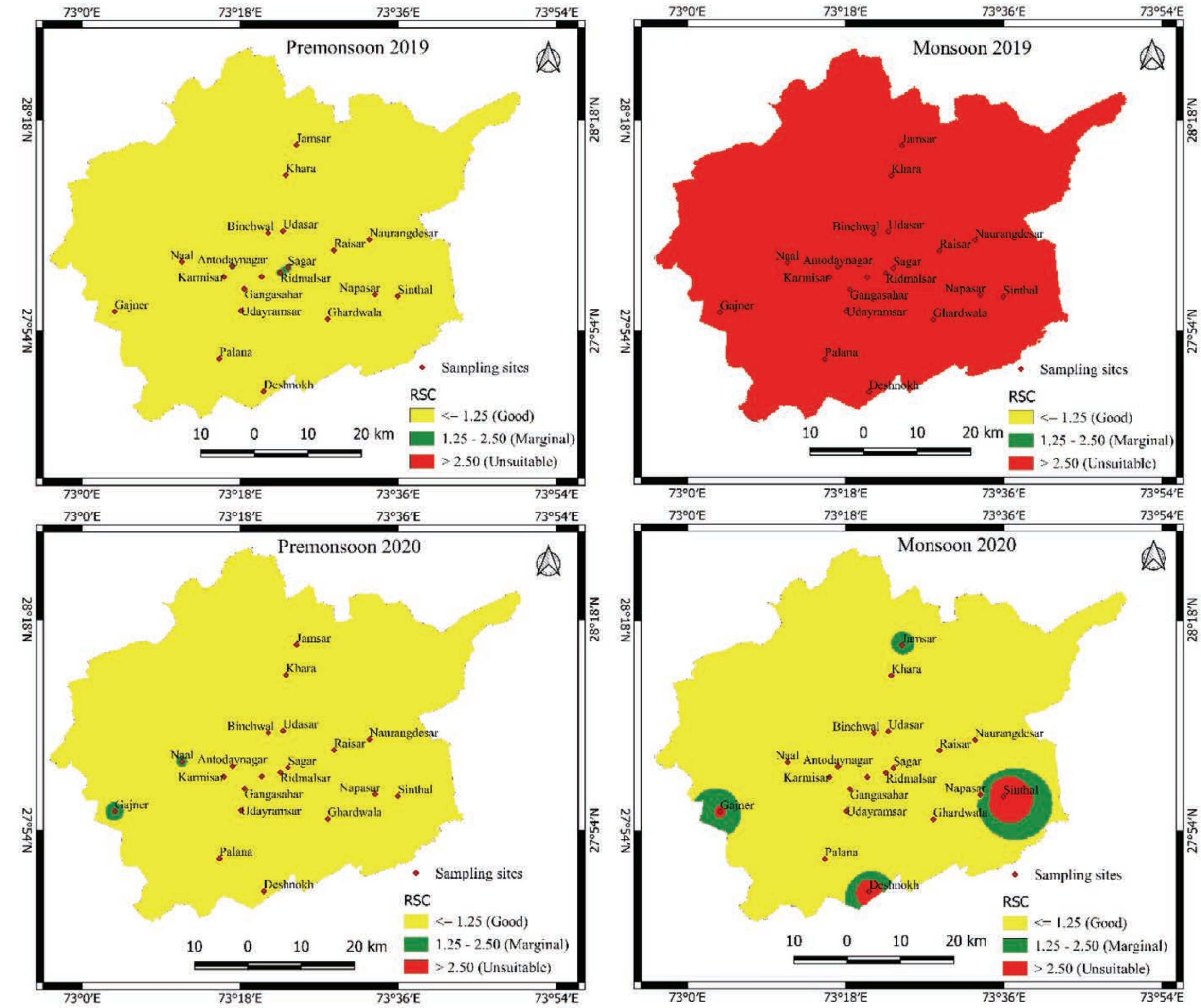


Figure 5. Spatial distribution of residual sodium carbonate (RSC) for irrigation quality in pre-monsoon and monsoon seasons of 2019 and 2020.

irrigation) were found in the western and southeastern parts during both seasons. RSC values less than 1.25 (good for irrigation) were observed in the central regions. In the pre-monsoon season, the RSC values are predominantly in the range of 1.25 to 2.50 (marginal) and greater than 2.50 (unsuitable) in many areas. High RSC values indicate that carbonate and bicarbonate ions in groundwater exceed calcium and magnesium ions, which can lead to soil sodicity and reduced soil permeability. Whereas, RSC values remain high during the monsoon seasons, with slight reductions in some areas. The slight reduction in RSC during the monsoon is due to the dilution effect of rainfall. However, the persistent high RSC values indicate that soil sodicity remains a concern for irrigation.

Spatial dispersal of magnesium absorption ratio (MAR) as displayed in Figure 6 in pre-monsoon seasons of 2019 and 2020 have MAR values generally high,

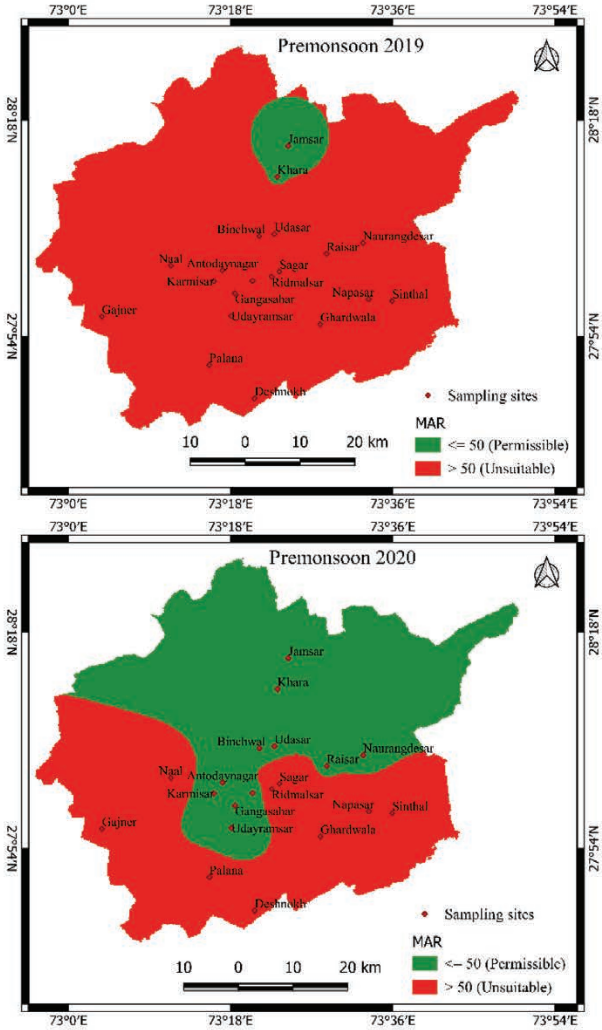


Figure 6. Spatial distribution of magnesium absorption ratio (MAR) for irrigation quality in pre-monsoon and monsoon seasons of 2019 and 2020.

with many areas showing values greater than 50, indicating unsuitable water quality for irrigation. MAR values greater than 50 were found in the southern and western areas during both seasons. MAR values less than 50 (permissible for irrigation) were observed in the northern and eastern regions. High MAR values indicate an excess of magnesium relative to calcium in groundwater, which can lead to poor soil structure and reduced crop yields. Areas with MAR values greater than 50 require careful management to ensure sustainable irrigation. MAR values show a slight decrease during the monsoon seasons, but many areas still have high values. The monsoon rainfall dilutes magnesium concentrations, but the persistent high MAR values indicate that magnesium-rich groundwater sources continue to impact irrigation water quality.

Figure 7 displays spatial dispersal of Kelly's ratio (KR) in pre-monsoon and monsoon seasons of 2019 and 2020. In pre-monsoon season, KR values are generally

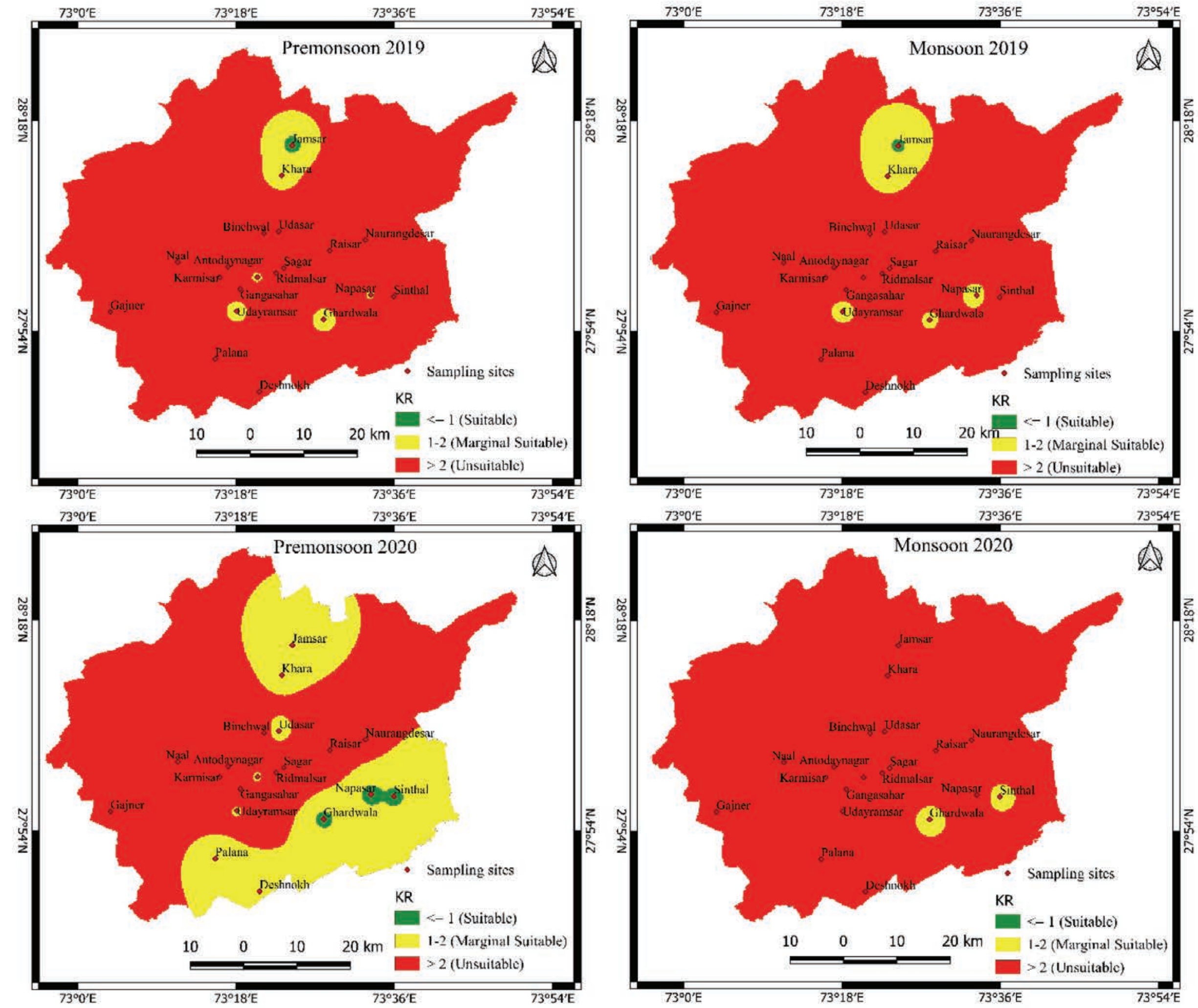


Figure 7. Spatial distribution of Kelly's ratio (KR) for irrigation quality in pre-monsoon and monsoon seasons of 2019 and 2020.

in the range of 1 to 2 (marginal suitable) and greater than 2 (unsuitable) in many areas. KR values greater than 2 were found in the southern regions during both seasons. Values less than 1 (suitable for irrigation) were observed in the central areas. High KR values indicate that sodium concentrations in groundwater exceed those of calcium and magnesium, which can affect soil structure and permeability. Areas with KR values greater than 2 require careful management to avoid adverse impacts on soil health. KR values show a slight decrease during the monsoon seasons, with some areas still showing high values. The monsoon rainfall dilutes sodium concentrations, but the persistent high KR values suggest that sodium remains a significant concern for irrigation.

Permeability index (PI) of pre-monsoon season of 2019 and 2020 are generally high (Figure 8), with many areas showing values greater than 50 (unsuitable).

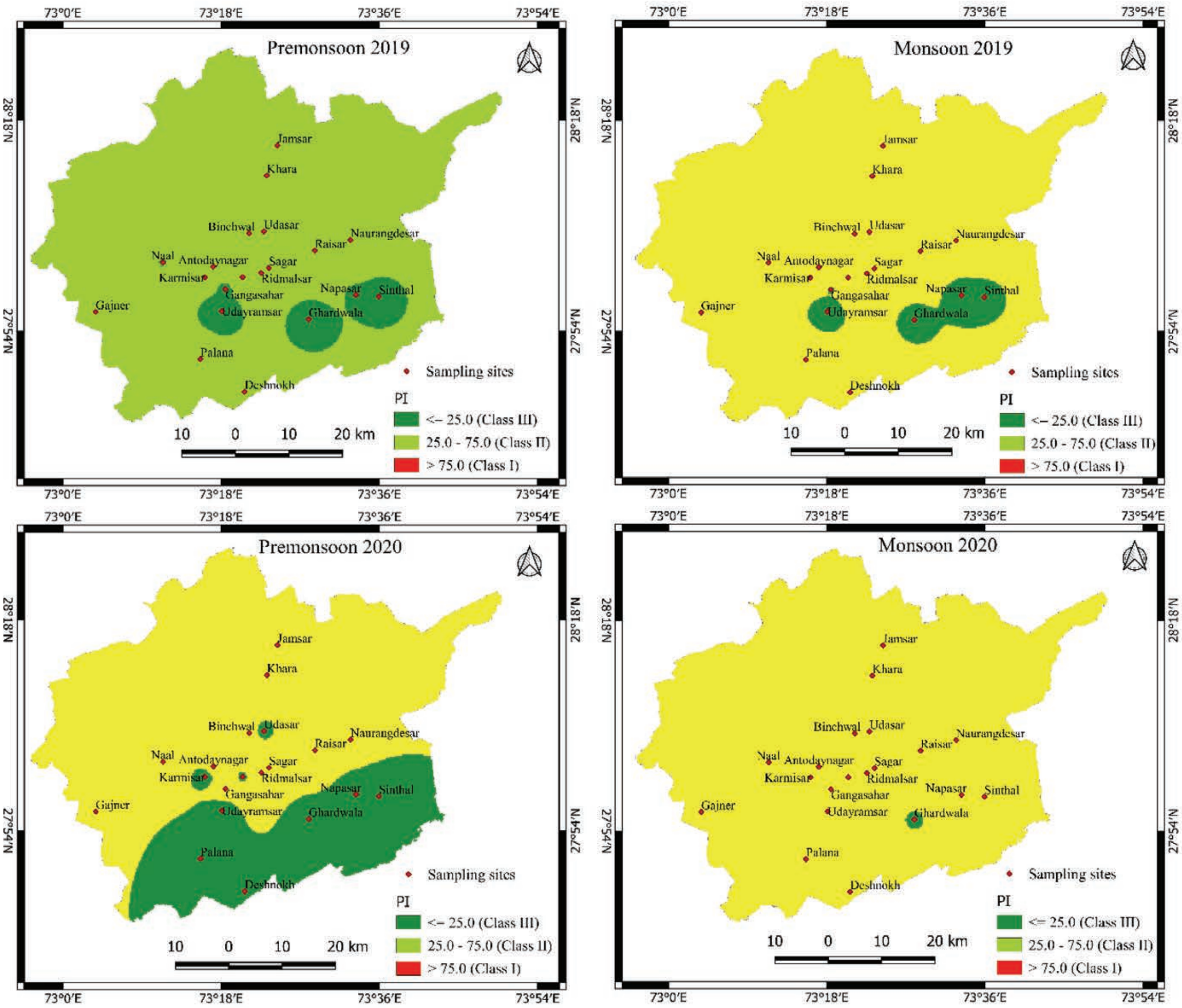


Figure 8. Spatial distribution of permeability index (PI) for irrigation quality in pre-monsoon and monsoon seasons of 2019 and 2020.

PI values greater than 75 (Class I, good permeability) were observed in the central and northern regions. PI values less than 25 (Class III, poor permeability) were found in the southern areas. High PI values indicate good groundwater permeability, while low PI values suggest poor permeability, which can affect irrigation efficiency. Areas with PI values greater than 50 require careful management to ensure sustainable irrigation. PI values show a slight decrease during the monsoon seasons, but many areas still have high values. The monsoon rainfall improves soil permeability to some extent, but the persistent high PI values indicate that groundwater sources continue to impact irrigation water quality.

Figure 9 displays spatial dispersal of potential salinity (PS) in pre-monsoon and monsoon seasons of 2019 and 2020. PS values greater than 10 (Class III, high

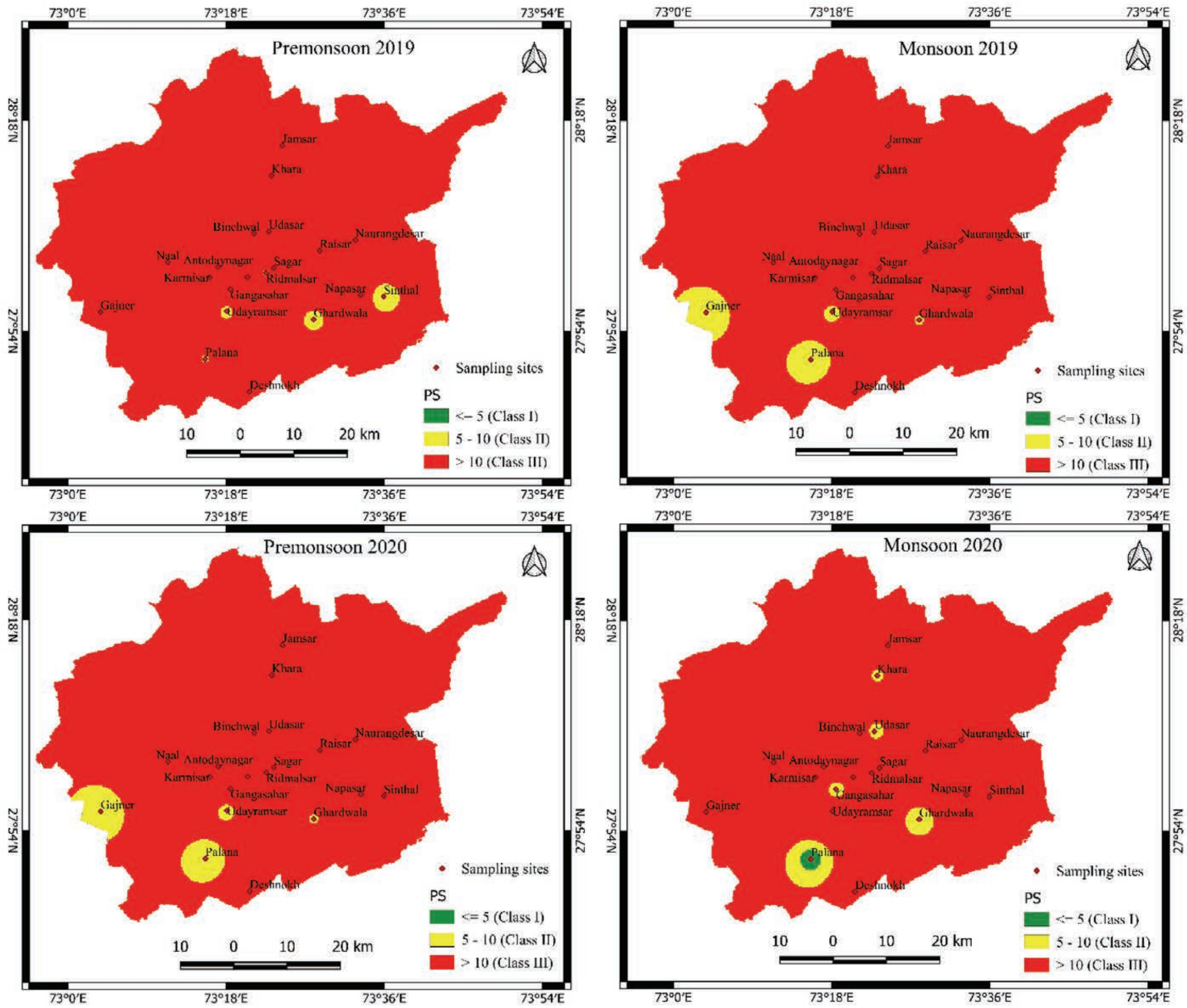


Figure 9. Spatial distribution of potential salinity (PS) for irrigation quality in pre-monsoon and monsoon seasons of 2019 and 2020.

salinity) were found in the western regions. PS values less than 5 (Class I, low salinity) were observed in the central and northern areas. In pre-monsoon season, PS values are generally high, with many areas showing values greater than 1 (unsuitable). High PS values indicate that groundwater has a high salinity level, which can affect soil structure and reduce crop yields. Areas with PS values greater than 1 require careful management to avoid adverse impacts on soil health. Though, PS values show a slight decrease during the monsoon seasons, but many areas still have high values. The monsoon rainfall dilutes salinity levels, but the persistent high PS values indicate that saline groundwater sources continue to impact irrigation water quality.

Corrosivity ratio (CR) distribution is depicted in Figure 10. CR values greater than 1 (unsuitable for irrigation) were observed in the southern regions. CR values less than 1 (suitable for irrigation) were found

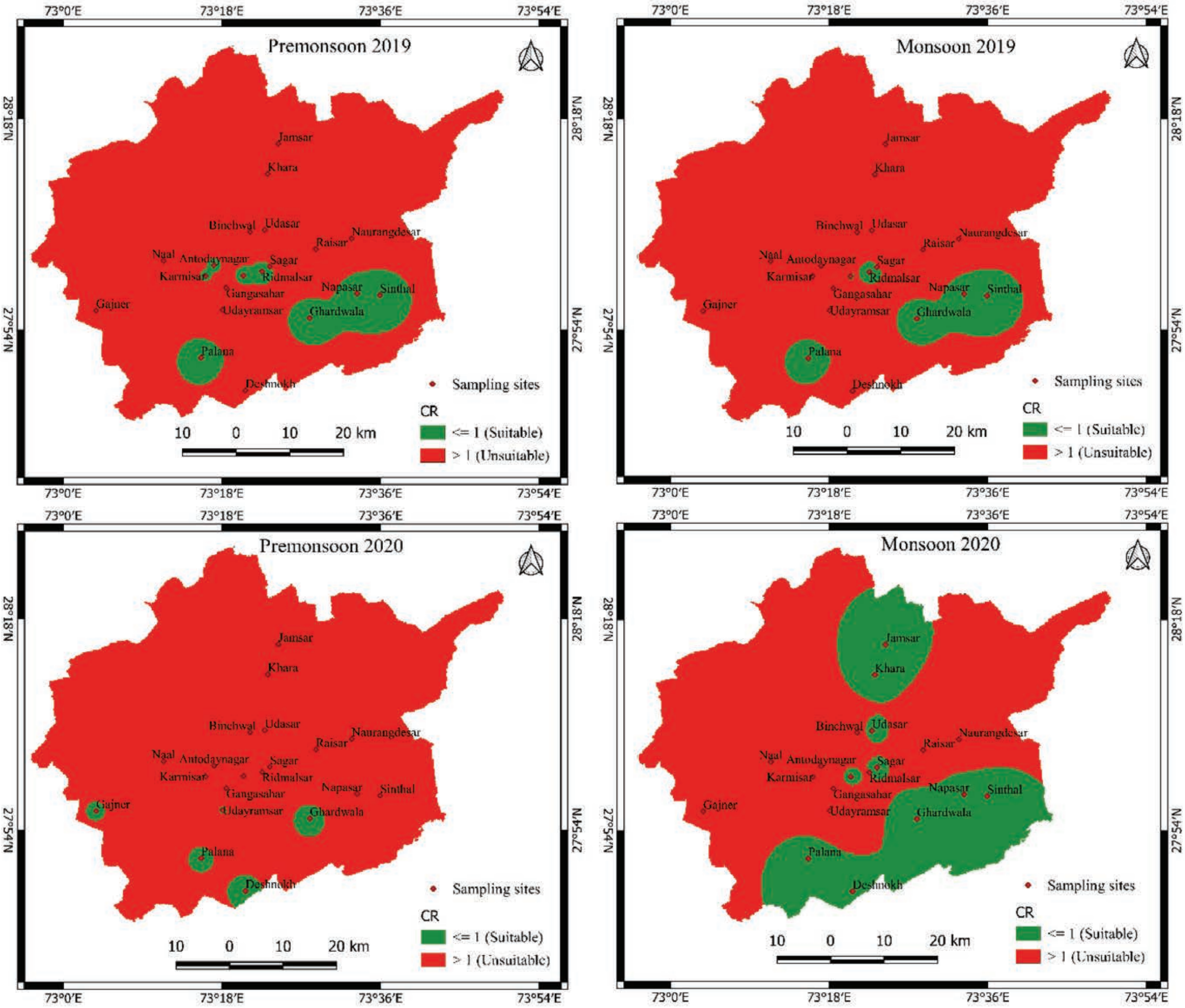


Figure 10. Spatial distribution of corrosivity ratio (CR) for irrigation quality in pre-monsoon and monsoon seasons of 2019 and 2020.

in the northern areas. CR values are generally high in pre-monsoon season, with many sites showing values greater than 1 (unsuitable). High CR values indicate that groundwater has a high potential for corrosiveness, which can affect irrigation infrastructure and soil health. Areas with CR values greater than 1 require careful management to ensure sustainable irrigation. CR values show a slight decrease during the monsoon seasons, but many areas still have high values. The monsoon rainfall reduces the corrosiveness of groundwater, but the persistent high CR values indicate that corrosive groundwater sources continue to impact irrigation water quality.

Chloro-alkaline indices (CAI-I and CAI-II) are shown in Figure 11 and Figure 12 respectively. Positive CAI-I and CAI-II values were found in the central and western regions, indicating ion exchange processes. Negative CAI-I and CAI-II values were observed in the

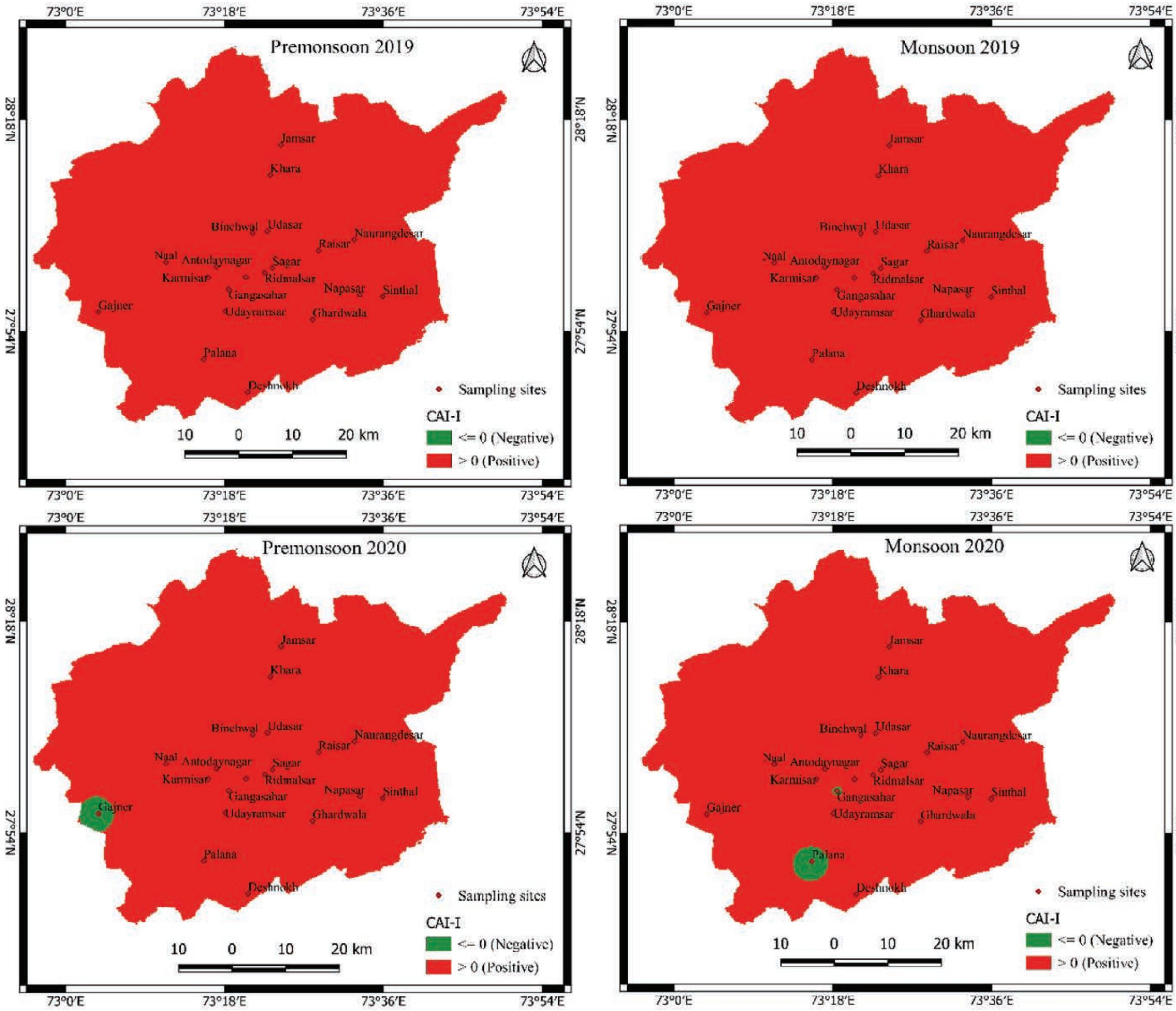


Figure 11. Spatial distribution of Chloroalkaline index (CAI-I) for irrigation quality in pre-monsoon and monsoon seasons of 2019 and 2020.

northern and southeastern areas, indicating reverse ion exchange. Positive CAI values suggest ion exchange processes, while negative values indicate reverse ion exchange, both affecting soil health.

In pre-monsoon of 2019 and 2020, CAI-I and CAI-II values are generally positive in many areas, indicating an exchange of sodium and potassium with calcium and magnesium in groundwater. Positive CAI values suggest that groundwater has undergone ion exchange processes, which can affect soil structure and permeability. Areas with positive CAI values require careful management to avoid adverse impacts on soil health. While in the monsoon season of 2019 and 2020, CAI-I and CAI-II values show a slight decrease during the monsoon seasons, but many areas still have positive values. The monsoon rainfall reduces the extent of ion exchange processes, but the persistent positive CAI values indicate that ion exchange continues to impact irrigation water quality.

Gibbs ratio (GR-II) is shown in Figure 13. GR-II values greater than 0.8 (unsuitable for irrigation) were found in the southern and western regions. GR-II values between 0.5 and 0.8 (suitable for irrigation) were observed in the central and northern areas. In pre-monsoon season of 2019 and 2020, GR-II values

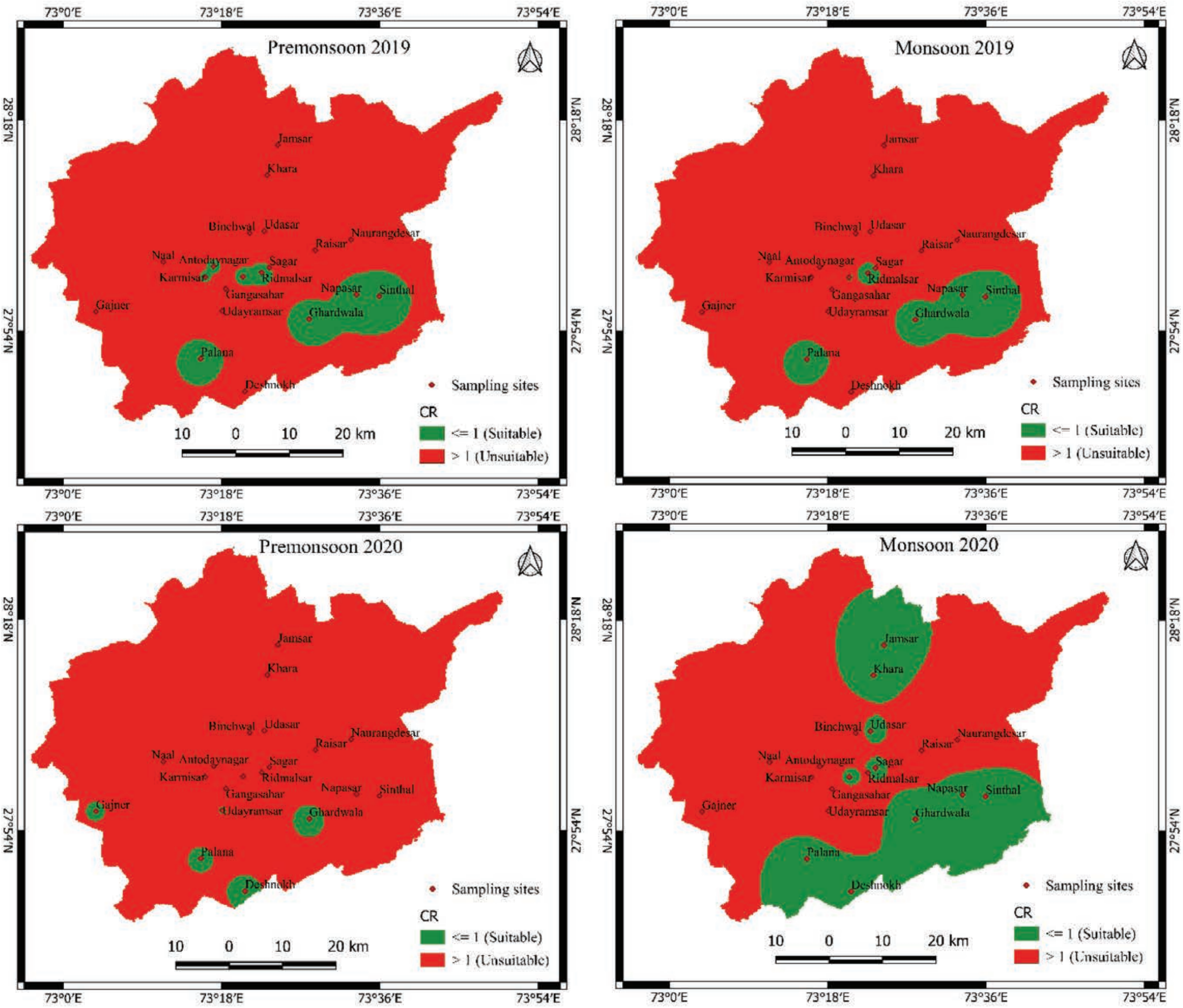


Figure 12. Spatial distribution of Chloroalkaline index (CAI-II) for irrigation quality in pre-monsoon and monsoon seasons of 2019 and 2020.

are generally high, with many areas showing values greater than 0.8 (unsuitable). High GR-II values indicate that groundwater has a high potential for salinization, which can affect soil structure and reduce crop yields. Areas with GR-II values greater than 0.8 require careful management to avoid adverse impacts on soil health. GR-II values show a slight decrease during the monsoon seasons, but many areas still have high values. The monsoon rainfall reduces salinization potential, but the persistent high GR-II values indicate that salinization remains a significant concern for irrigation.

The spatial distribution maps of irrigation parameters demonstrate the southern and western regions exhibit high SAR, RSC, MAR, KR, PS, and GR-II values, indicating poor groundwater quality for irrigation due to high sodium, salinity, and magnesium levels. The central regions exhibit marginally suitable for irrigation as the area show moderate values, requiring careful management to maintain soil health and irrigation efficiency. The northern regions generally show lower values for SAR, RSC, MAR, KR, PS, CR, and GR-II, indicating better water quality with lower salinity, sodium, and other contaminants, making them more favourable for agricultural use. Overall, groundwater in the southern and western regions of the study area is largely unsuitable for irrigation due to high sodium, salinity, and magnesium levels. The central regions require careful management. While, northern region is suitable for irrigation.

Table 7 shows United States Department of Agriculture (USDA) salinity classification of the groundwater based on EC and TDS (Chahal et al. 2023). C1 class water can cause low hazard with no salt accumulation in soil and no harmful effects on plants. In C2 class, salt accumulation in soil can be prevented due to moderate leaching and sensitive plants show salt stress. C3 class water requires careful irrigation, good drainage, and leaching. Salinity affects most plants and salt-tolerant plants can grow well. C4 class water is unsuitable for irrigation and highly salt-resistant plants can grow. Hence, water need to be drained exceptional with frequent leaching, and rigorous management. In 2019, 65 % samples are

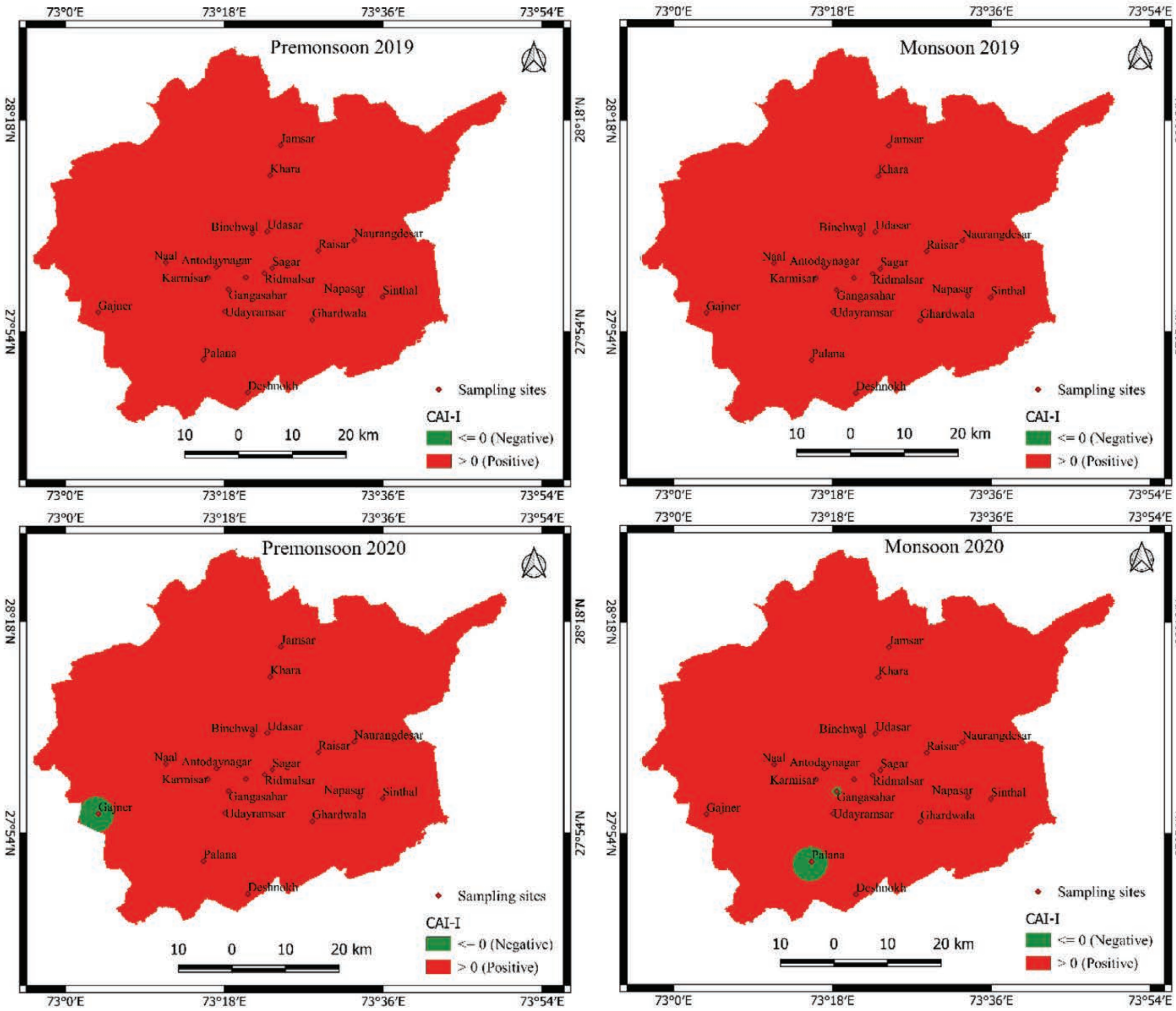
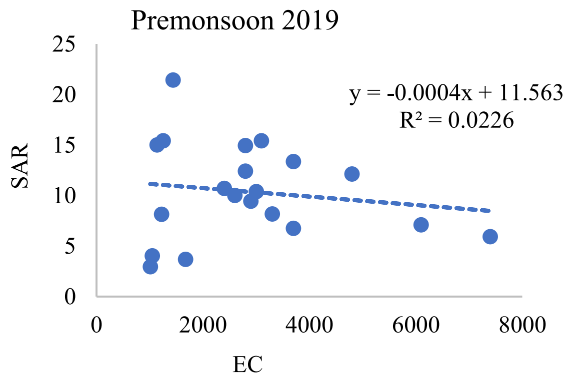


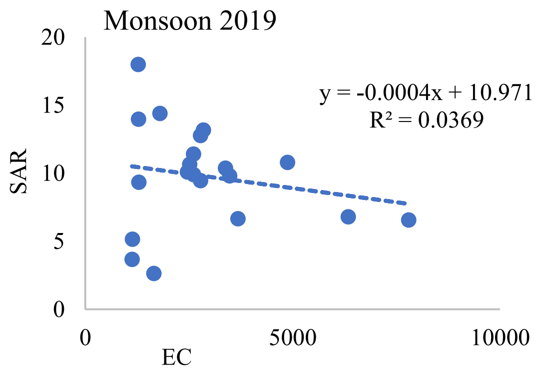
Figure 13. Spatial distribution of Gibbs ratio (GR-II) for irrigation quality in pre-monsoon and monsoon seasons of 2019 and 2020.

Table 7. USDA classification of study area groundwater based on EC and TDS.

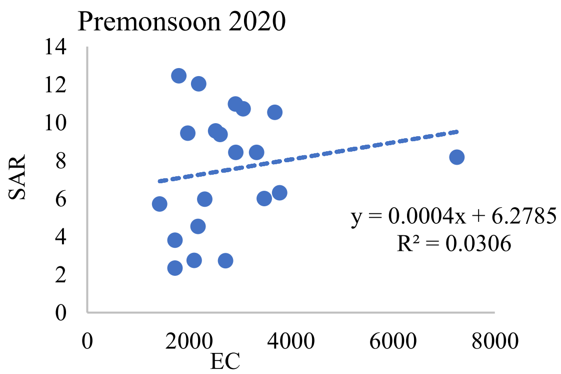
Class		C1	C2	C3	C4
EC (µS/cm)		<250	250-750	750-2250	>2250
TDS (mg/L)		<150	150-500	500-1500	>1500
Number of samples	Premonsoon-2019	NIL	NIL	7	13
	Monsoon 2019	NIL	NIL	7	13
	Premonsoon-2020	NIL	NIL	8	12
	Monsoon 2020	NIL	NIL	5	15
Percentage of samples	Premonsoon-2019	NIL	NIL	35	65
	Monsoon 2019	NIL	NIL	35	65
	Premonsoon-2020	NIL	NIL	40	60
	Monsoon 2020	NIL	NIL	25	75



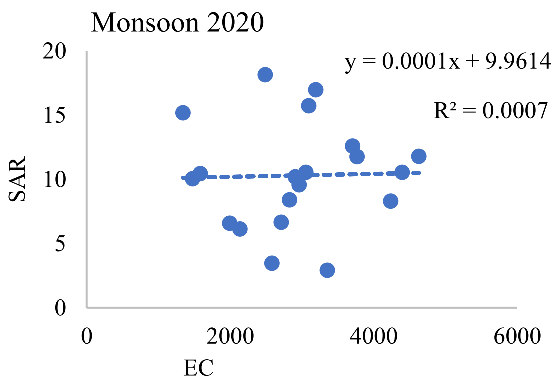
(a) Pre-monsoon 2019



(b) Monsoon 2019



(c) Pre-monsoon 2020



(d) Monsoon 2020

Figure 14. Relationship between SAR and EC.

under C4 category and 35 % samples are in C3 category. While, in 2020, 60 % samples of pre-monsoon are in C4 class and 75 % samples of monsoon falls under C4 class. There are no sample falls under class C1 and C2 of the study area, demonstrating highly saline water.

The relationship between salinity (EC) and sodicity (SAR) is important in understanding soil health and plant growth. High salinity can affect plant growth by reducing the ability of plants to take up water. High sodicity can lead to soil dispersion, where soil particles separate and clog soil pores, reducing water infiltration and root growth. The combination of EC and SAR determines soil swelling and dispersion possibility. A balanced EC and SAR is crucial for maintaining good soil structure and ensuring proper water movement through the soil. Figure 14 (a-d) illustrates the relationship between SAR and EC of pre-monsoon 2019, monsoon 2019, pre-monsoon 2020 and monsoon 2020. R-squared values of 0.0226, 0.0369, 0.0306 and 0.0007 are obtained for pre-monsoon 2019, monsoon 2019, pre-monsoon 2020 and monsoon 2020 respectively which are positive and low, representing greater variations in electrical conductivity compared to sodium absorption ratios of the groundwaters. The relationships reveal both salinity and sodicity management is essential for maintaining soil physical properties and promoting optimal plant growth.

Correlation matrix of irrigation parameters:

The correlation matrix of selected irrigation parameters is presented in Table 8. The value of Pearson correlation coefficient (r) of more than 0.5 is strong and positive correlation. While correlation coefficient value of 0.3 to 0.5 is moderately positive and less than 0.3 value is a weakly positive correlation. The highest positive correlation is 0.99 which is found between CAI-II with PS and CA-II with CAI-I. CAI-I have 0.98 correlation with PS. Sodium to calcium ratio is correlated to KR (0.94). Similarly, magnesium to calcium ratio is strongly positively related to MAR (0.93). GR-II with percentage sodium has 0.92 correlation. Kelly's ratio is strongly correlated to sodium absorption ratio (0.91). Strong and positive correlation is also observed between SAR and %Na (0.88), KR and %Na (0.88), Na : Ca with SAR (0.87), Cl : HCO_3 with CAI-I (0.84) and HCO_3 with CAI-II (0.81).

The findings of the present study are compared with other recent studies in India as shown in Table 9.

International research studies on groundwater suitability for irrigation purposes is also realted with the present study. Zazouli et al. (2024) assessed groundwater quality of Behshahr-Galougah plain (southern coast of the Caspian Sea) of Iran. The study

Table 8. Correlation matrix of irrigation parameters of groundwater.

	EC	NO3-	Na (%)	SAR	RSC	MAR	KR	PI	PS	CR	CAI - I	CAI - II	GR-I	GR-II	Cl/HCO3	Mg/Ca	Na/Ca
EC	1																
NO3-	-0.07	1.00															
Na (%)	-0.22	0.11	1.00														
SAR	-0.06	-0.03	**0.88**	1.00													
RSC	-0.69	0.09	0.54	0.25	1.00												
MAR	-0.25	0.29	0.17	0.19	0.31	1.00											
KR	-0.23	-0.01	**0.88**	**0.91**	0.46	0.16	1.00										
PI	0.44	-0.11	0.35	**0.61**	-0.36	-0.07	0.33	1.00									
PS	**0.76**	-0.05	-0.25	-0.05	-0.66	-0.13	-0.24	0.45	1.00								
CR	**0.67**	-0.06	-0.36	-0.17	-0.81	-0.34	-0.31	0.30	**0.75**	1.00							
CAI – I	**0.69**	-0.04	-0.22	-0.05	-0.56	-0.04	-0.23	0.39	**0.98**	**0.64**	1.00						
CAI - II	**0.72**	-0.02	-0.27	-0.11	-0.57	-0.07	-0.28	0.37	**0.99**	0.66	**0.99**	1.00					
GR-I	0.40	-0.02	-0.09	0.00	-0.36	0.02	-0.11	0.18	**0.67**	0.45	**0.74**	**0.67**	1.00				
GR-II	-0.31	0.22	**0.92**	**0.78**	**0.62**	0.49	**0.77**	0.24	-0.30	-0.49	-0.24	-0.28	-0.08	1.00			
Cl/HCO3	**0.58**	-0.10	-0.11	0.03	-0.52	-0.07	-0.15	0.33	**0.83**	**0.63**	**0.84**	**0.81**	**0.79**	-0.14	1.00		
Mg/Ca	-0.11	0.32	0.06	0.11	0.15	**0.93**	0.05	-0.02	-0.06	-0.23	0.01	-0.02	0.05	0.38	-0.05	1.00	
Na/Ca	-0.24	0.06	**0.80**	**0.87**	0.42	0.43	**0.94**	0.31	-0.21	-0.30	-0.19	-0.25	-0.07	**0.78**	-0.14	0.34	1

Table 9. Comparison of the current findings with other studies.

Location	Irrigation parameters used	Findings	References
Udham Singh Nagar, Uttarakhand	Sodium adsorption ratio, soluble sodium percentage, residual sodium carbonate, magnesium hazard, permeability index, chloro-alkaline index values	Groundwater was alkaline, hard, and suitable for irrigation based on several criteria, but 54% samples were unsuitable for irrigation as per magnesium hazard.	Singh et al. (2020)
Edappadi, Tamil Nadu	Nitrate, fluoride, salinity	Groundwater was marginally alkaline, high saline to very high saline and was unsuitable for crop production due to salinity.	Karunanidhi et al. (2021)
Northeastern Rajasthan	Fluoride, nitrate	85% water samples above permissible limit for fluoride which causes risks of dental, knee, hip bone deformities, and crippling fluorosis.	Keesari et al. (2021)
Mid-Gangetic plain, Uttar Pradesh	EC, TDS, bicarbonate, phosphate, ammonium, sodium percentage, SAR, SSP, RSC, magnesium hazard, permeability index	Groundwater was suitable for irrigation except for magnesium hazard and permeability index.	Tripathi et al. (2023)
Panipat, Haryana	% Na, SAR, RSC, KR, PI, Mg:Ca ratio	Groundwater was mainly alkaline, hard to very hard and fresh to very brackish. Seasonal variation was highly affected by human activities.	Chahal et al. (2023)
Sangli, Maharashtra	Magnesium hazard (MH), Kelley's ratio (KR), sodium absorption ratio (SAR)	134 samples were unsuitable for agricultural irrigation.	Sathe et al. (2024)
Kurukshetra, Haryana	Alkalinity, hardness, magnesium, sodium percentage, sodium adsorption ratio, Kelly's ratio, permeability index, corrosivity ratio	Groundwater was unsuitable for irrigation based on several categories.	Bhatnagar & Thakral (2024)
Jammu and Samba districts, J&K	Physicochemical parameters, corrosivity ratio	Groundwater was suitable for drinking, irrigation, and industrial uses.	Kumar et al. (2024)
Kapurthala, Punjab	Electrical conductivity, sodium adsorption ratio, residual sodium carbonate, percentage sodium, water quality index	Groundwater was suitable for irrigation based on several indices and was affected by seasonal changes.	Singh et al. (2024)
Sundargarh district, Odisha	EC, TDS, CI, %Na, SSP, SAR, ESP, MH, RSC, KR, PI, PS	Groundwater was highly suitable for irrigation and controlled by evaporation, reverse ion exchange, silicate weathering.	Shaw & Sharma (2024)
Bikaner, Rajasthan	EC, TDS, nitrate, %Na, SAR, MAR, RSC, KR, PI, PS, chloro-alkaline indices	Groundwater was unsuitable for irrigation due to high values of EC, salinity, nitrate, MAR, KR, PS and $Cl:HCO_3$	Present study

revealed that nitrate concentrations was ranged from 0.05 mg/L to 200 mg/L, primarily attributed to wastewater effluents and agricultural activities in the region. Residual sodium bicarbonate was in the permissible category for irrigation. Low to very low SAR values was shown by more than 98% samples. While, more than 94% of groundwater samples showed sodium percentage in permissible to excellent levels. Most samples fell in suitable category of permeability index and magnesium absorption ratio. Overall, the groundwater quality in the Behshahr-Galougah plain remains favorable for agricultural applications, with minimal concerns regarding sodium hazards (El-Defan et al. 2016). Soomro et al. (2024) assessed irrigation quality of groundwater in rural Hyderabad of Pakistan. Elevated EC (26%), calcium (87%), magnesium (89%), and sodium (60%) concentrations suggested potential salinity risks. Conversely, carbonate, bicarbonate, chloride, sulfate, and nitrate levels largely fell within acceptable limits. Irrigation quality indices such as SAR, soluble sodium percentage, residual sodium carbonate, and permeability index confirmed suitability for irrigation. Notably, magnesium hazard and Kelley's ratio indicated favorable conditions in 78% and 85% of samples respectively. The U.S. Salinity Laboratory (USSL) classification categorized 65% samples into C3S1, 22% into C2S1 and 11% into C4S1 groups, indicative of varying degrees of salinity influence. Additionally, Gibbs ratios demonstrated evaporation dominance, indicating the regional climate's significant role in groundwater composition. Chloralkaline Index (CAI) values further suggested positive ion exchange, commonly observed in arid regions. While groundwater in rural Hyderabad generally supports irrigation, localized areas with higher salinity risks may prove unsuitable for crops with low salt tolerance. Guo et al. (2021) assessed groundwater irrigation suitability in the North China Plain and indicated that salinity and sodium hazards have influence on groundwater usability in agricultural settings. The values of SAR, Na%, and RSC approve the applicability of shallow (20-150 meters) groundwater for agricultural use. High salinity levels were detected in 57.1% of shallow groundwater samples, posing potential challenges for long-term soil health by degrading soil permeability. Al Maliki et al. (2020) investigated groundwater suitability for irrigation near Al Kufa City, Iraq and found the maximum values of TDS, EC, Na, and K were 3630 mg/L, 7260 µS/cm, 869 mg/L, and 408 mg/L respectively. All groundwater samples over the study area were suitable for agricultural irrigation. Benam-Beltoungou et al. (2025) evaluated groundwater quality in the Thiaroye aquifer of Senegal. The values of irrigation indices suggest that groundwater is unsuitable for long-term agricultural use. Evaluation of Groundwater suitability for irrigation in the northwestern part of Kano State (Nigeria) was done by Adagba et al. (2022). SAR values ranging between 0.00 and 10.99 provide insights into sodium-related risks affecting soil permeability. Similarly, percentage sodium values (26 % to 94.42%) play a crucial role in defining sodium toxicity in agricultural landscapes. The Permeability Index (94.14% to 379.47%) suggests variations in the groundwater's ability to maintain soil porosity. Kelly Ratio (0.0 to 8.62) and magnesium hazard (0.0% to 80.33%) highlight concerns related to excess magnesium levels in water, which can negatively impact soil structure over time. Total hardness of groundwater (12.49 mg/L to 77.50 mg/L) is within permissible limits. RSC (-0.55 meq/L to 5.46 meq/L) provides further evidence of the water's suitability for irrigation. Potential Salinity (0.88 meq/L to 2.53 meq/L) and Electrical Conductivity (110 µS/cm to 910 µS/cm) determined the long-term implications of mineral accumulation in soil. In general, groundwater was suitable for agricultural irrigation with minimal risk of salinity related damage.

These studies illustrate a global trend toward using integrated, data-driven approaches for evaluating groundwater quality for irrigation. Recent advances in GIS-based interpolation and irrigation water indices provide valuable tools for evaluating groundwater suitability in agricultural regions. Continued monitoring and refinement of assessment methods, particularly incorporating climate variability and soil-water interactions, will be critical in ensuring sustainable groundwater use. Future research could further explore seasonal variations, the effects of anthropogenic activities, and the long-term impacts of climate change on groundwater quality.

Conclusions

Assessment of ground water for irrigation water quality parameters illustrates that electrical conductivity of high salinity (751 to 2250 µS/cm) and very high salinity (more than 2250 µS/cm) were found. High salinity is shown by 5 and 8 samples of monsoon and pre-monsoon season of 2020. The categories of high and very high salinity are exhibited by 72.5% samples of each pre-monsoon and monsoon seasons. Similarly, more than 30 mg/L of nitrate concentration of high category was found in 72.5% samples of pre-monsoon and 85% samples of monsoon seasons. Low nitrate concentration (less than 5 mg/L) was not detected. All the samples had less than 60% sodium percentage which is permissible for irrigation purposes. A considerable portion of samples, comprising 62.5% from pre-monsoon and 47.5% from monsoon season demonstrated low SAR values with range of 0 to 10. Very high SAR category (more than 26) was not detected. Residual sodium content of less than 1.25 (good category) was seen in 82.5% samples of pre-monsoon and 87.5% samples of monsoon. Permissible magnesium absorption ratio of less than 50 was observed in 32.5% samples of pre-monsoon and 30% samples of monsoon. Though, 67.5% samples of pre-monsoon and 70% samples of monsoon had more than 50 magnesium absorption ratio which comes under unsuitable for irrigation category. Kelly's ratios were also found of unsuitable category (more than 2) in 60% samples of pre-monsoon and 77.5% samples of monsoon season. Permeability index of class I (more than 75%) is maximum permeability which was not assessed in any sample. Most samples showed permeability index of class II with 25 to 75% permeability (62.5% samples of pre-monsoon and 72.5% samples of monsoon). Potential salinity of most samples falls under class III (less than 10) which is injurious and unsatisfactory for irrigation (70% samples of each pre-monsoon and monsoon seasons). Corrosivity ratio of less than 1 was observed in 67.5% samples of pre-monsoon and 57.5% samples of monsoon, indicating water is safe for transportation through any type of pipes. Most of the samples had positive chloro-alkali indices CAI-I and CAI-II. Most samples showed Cl: HCO_3 ratio of more than 6.6 which comes under highly contaminated class. Overall, 62.5% samples of pre-monsoon and 70% samples of monsoon season were detected unsuitable for irrigation chiefly because of highly saline groundwater. It is recommended to do continuous monitoring of groundwater of study area. The study is helpful for selection of suitable crops according to quality of irrigation water as well as for framing policy by decision makers.

References

Adagba, T., Kankara, A. I., Idris, M. A. (2022). Evaluation of groundwater suitability for irrigation purpose using GIS and irrigation water quality indices. FUDMA *Journal of Sciences*, **6**: 63-80.

Al Maliki, A. A., Abbass, Z. D., Hussain, H. M., Al-Ansari, N. (2020). Assessment of the groundwater suitability for irrigation near Al Kufa City and preparing the final water quality maps using spatial distribution tools. *Environmental Earth Science*, **79**: 330.

APHA. (2017). *Standard methods for the examination of water and waste water*. 22nd Edition, American Public Health Association, American Water Works Association, Water Environment Federation.

Begum, T., Shareef, A., Rafique, T., Khwaja, H. A. (2024). Assessment of groundwater quality with special emphasis on fluoride contamination: a case study in Thar Desert, Pakistan. *Sustainable Water Resources Management*, **10**: 53.

Benam-Beltoungou, E. Y. T., Bassene, I., Emvoutou, H. C., Akpataku, K. V., Diongue, D. M. L., Faye, S. (2025). Groundwater quality assessed using water quality indices and geostatistical methods in the Thiaroye aquifer, Senegal. *Water Science*, **39**: 151-170.

Bhatnagar, A. & Thakral, N. (2024). Assessment of groundwater quality for drinking and irrigation purposes using hydro-chemical and water quality index studies in Kurukshetra (Haryana), India. *Water, Air, and Soil Pollution*, **235**: 351.

Chahal, S., Gautam, S. K., Paulraj, R. (2023). Hydrogeochemical characterization and assessment of water suitability for irrigation in salt-affected area of Israna block, Haryana, India. *Water Conservation Science and Engineering*, **8**: 20.

Eaton, F. M. (1950). Significance of carbonates in irrigation waters. *Soil Science*, **69**: 123-134.

Ekbal, E. & Khan, T. A. (2022). Hydrogeochemical characterization of groundwater quality in parts of Amroha District, Western Uttar Pradesh, India. *HydroResearch*, **5**: 54-70.

El-Defan, A., El-Raies, S., El-Kholy, H., Osman, A. (2016). A summary of water suitability criteria for irrigation. *Journal of Soil Sciences and Agricultural Engineering*, **7**: 981-989.

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

Guo, H., Li, M., Wang, L., Wang, Y., Zang, X., Zhao, X., Wang, H., Zhu, J. (2021). Evaluation of groundwater suitability for irrigation and drinking purposes in an agricultural region of the North China Plain. *Water*, **13**: 3426.

Karunanidhi, D., Aravinthasamy, P., Subramani, T., Setia, R. (2021). Groundwater suitability estimation for sustainable drinking water supply and food production in a semi-urban area of south India: A special focus on risk evaluation for making healthy society. *Sustainable Cities and Society*, **73**: 103077.

Keesari, T., Pant, D., Roy, A., Sinha, U. K., Jaryal, A., Singh, M., Jain, S. K. (2021). Fluoride geochemistry and exposure risk through groundwater sources in northeastern parts of Rajasthan, India. *Archives of Environmental Contamination and Toxicology*, **80**: 294-307.

Kelley, W. P. (1963). Use of saline irrigation water. *Soil Science*, **95**: 385-391.

Khuhawar, M. Y., Ursani, H., Khuahwar, T. M. J., Lanjwani, M. F., Mahessar, A. A., Tunio, I. A., Soomro, A. G., Rind, I. K., Brohi, R., Khuhawar, A. H., Solangi, S. H., Soomro, R., Kandhro, A. J., Pathan, A. S. (2019). Assessment of water quality of groundwater of Thar Desert, Sindh, Pakistan. *Journal of Hydrogeology and Hydrologic Engineering*, **7**: 2.

Kumar, R., Sharma, S., Prashant, M. (2024). Assessment of groundwater quality for drinking, irrigation and industrial purposes in Aik Watershed, Jammu and Kashmir, India. *Discover Geoscience*, **2**: 58.

Raghunath, H. M. (2007). *Groundwater* (3rd edition). 520 pp. New Age International Private Limited.

Richards, L. A. (1954). *Diagnosis and improvement of saline and alkali soils*. Handbook. 60 pp. US Department of Agriculture, Washington, DC.

Sathe, S. S., Bhan, U., Kushwaha, A., Shabbir, M., Patil, K., Kamboj, V., Goswami, L., Oh, S., Bahukhandi, K. D., Bind, A. (2024). Fluoride distribution, groundwater quality and health risk assessment for contaminated region near Krishna River (Maharashtra) India. Environmental Nanotechnology, *Monitoring and Management*, **23**: 101033.

Schoeller, H. (1977). Geochemistry of groundwater. In: Brown, R. H., Konoplyantsev, A. A., Ineson, J., Kovalevsky, V. S. (eds). *Groundwater Studies*: An international guide for research and practice, 1-18. UNESCO, Paris.

Sellamuthu, S., Joseph, S., Gopalakrishnan, S., Sekar, S., Khan, R., Shukla, S. (2022). Appraisal of groundwater quality for drinking and irrigation suitability using multivariate statistical approach in a rapidly developing urban area, Tirunelveli, India. *Environmental Science and Pollution Research*, **2022**: 1-17.

Shaw, S. K. & Sharma, A. (2024). Assessment of groundwater quality and suitability for irrigation purpose using irrigation indices, remote sensing and GIS approach. *Groundwater for Sustainable Development*, **26**: 101297.

Singh, K. K., Tewari, G., Kumar, S. (2020). Evaluation of groundwater quality for suitability of irrigation purposes: A case study in the Udham Singh Nagar, Uttarakhand. *Journal of Chemistry*, **2020**: 6924026.

Singh, A. P. & Bhakar, P. (2021). Development of groundwater sustainability index: a case study of western arid region of Rajasthan, India. Environment, *Development and Sustainability*, **23**: 1844-1868.

Singh, G., Singh, J., Wani, O. A., Egbueri, J. C., Agbasi, J. C. (2024). Assessment of groundwater suitability for sustainable irrigation: A comprehensive study using indexical, statistical, and machine learning approaches. *Groundwater for Sustainable Development*, **24**: 101059.

Soomro, S. A., Hao, L., Memon, G. A., Junejo, A. R., Niu, W., Channa, Z. A., Chandio, M. K., Channa, J. A., Alkahtani, J., Dahri, J. (2024). Comprehensive analysis of groundwater suitability for irrigation in Rural Hyderabad, Sindh, Pakistan. *Agronomy*, **14**: 1072.

Szabolcs, I. (1964). The influence of irrigation water of high sodium carbonate content on soils. *Agrokémia és Talajtan*, **13**: 237-246.

Tripathi, P., Kumar, M., Bhagat, C., Jha, P. K. (2023). Assessment of hydrochemical shift in riverine aquifers of the mid-Gangetic plain of Uttar Pradesh, India. *Groundwater for Sustainable Development*, **22**: 100965.

Wilcox, L. V. (1955). *Classification and use of irrigation water*. Circular 969, US Department of Agriculture, Washington, DC.

Zazouli, M. A., Dashtban, N., Jalalvand, M. A., Kheilgavan, S. J., Mashhadi Kholerdi, F., Mohammadpour, A., Rahman, M. M., Krause, S., Dehbandi, R. (2024) Unveiling nitrate contamination and health risks: Insights from groundwater quality assessment and Monte Carlo simulation along the Southern Caspian Sea Coasts. *Groundwater for Sustainable Development*, **27**: 101340.