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ORIGINAL ARTICLE

Hydrochemical and quality assessment of irrigation water at the trans-himalayan high-altitude regions of Leh, Ladakh, India

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Abstract

A total of seventy irrigation water samples were collected from Leh, Ladakh, India, to determine their hydrochemistry profile and water quality for irrigation purposes. Water quality indices such as total hardness (TH), residual sodium carbonate (RSC), potential salinity (PS), permeability index (PI), Kelly's ratio (KR), sodium absorption ratio (SAR), corrosivity ratio (CR), and chloroalkaline indices (CAI) were measured. The Piper diagram, Durov's diagram, and United States Salinity Laboratory (USSL) diagram were drawn to determine the water types, ion exchange processes, and rock–soil–water interaction. The findings indicated that the hydrochemical characteristics of irrigation water are naturally alkaline. Furthermore, water quality parameters revealed that the study area's surface water is suitable for irrigation purposes, despite relatively high TH and MH levels. The level of CR indicated that water should not be transported using metal pipes. The CAI and Durov's plot indicated direct ionic exchange processes controlling water chemistry. Additionally, this irrigation water is mainly dominated by the Ca^{2+}–Cl^-–SO_4^{2-}, Na^+–K^+–$CaCO_3 + HCO_3^-$, and Na^+–K^+–Cl^- type, which indicates silicate rock weathering along with some anthropogenic input. The USSL salinity diagram indicated a medium salinity and low Na hazard. Hence, it is concluded that the rock weathering cycle is the natural source of all the cations and anions, and these ions pass directly from water to rock and *vis*-à-*vis,* along with some input of anthropogenic activity.

Keywords Irrigation water · High altitude · Water–rock interaction · Water quality

Introduction

The cross talk between soil properties and irrigation water chemistry, apart from other factors, plays a significant role in agricultural yields (Tesfahunegn and Gebru 2020). Irrigation water chemistry is mainly determined by the Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, and HCO_3^- levels, and therefore, these ions affect the level of residual sodium carbonate (RSC), potential salinity (PS), permeability index (PI), Kelly's ratio (KR), magnesium hazard (MH), sodium percentage (Na percent), sodium absorption ratio (SAR), corrosivity ratio (CR), and chloroalkaline indices (CAI) in irrigation water (Nag and Suchetana 2015; Pant et al. 2018; Rawat et al. 2018). Further, some studies revealed that irrigation water has higher macro- and microelements in arid regions (Elgallal et al. 2016; Mehmood et al. 2019). Hence, simple interpretations obtained using these water quality indices are essential for comprehensive irrigation water management in agricultural practices (Tyagi et al. 2014).

Environmental change has impacted social life, the pattern of the agro-animal cluster, the weathering cycle, and the groundwater and surface water quality (New 2009; Bharti et al. 2017a; Ghezzi et al. 2017; Singh et al. 2017; Pant et al. 2018; Giri 2019; Murali et al. 2020; Giri et al. 2020). High-altitude areas are more vulnerable to food security since 12% of the global human population suffers from the impact of global warming (Skoet et al. 2006; Lamprecht et al. 2018; Convey and Peck 2019). Recent studies reported that climate change in the semiarid areas of Ethiopia would reduce crop production (maize) by up to 40% by the year 2080 (Muluneh et al. 2015; Muluneh 2020). Most other high-altitude areas, like the Kyrgyz Tien Shan, the Mongolian Altai, the Tibetan

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Plateau, the Central Asian highlands, and so on, are also seeing similar changes (Huang et al. 2009; Asian Development Bank 2010; Kerven et al. 2011; Murali et al. 2020).

Ladakh, the land of high passes, is a high-altitude trans-Himalayan region with great strategic importance. The Indus, Shyok, and Zanskar rivers are the major rivers flowing through this region (Giri et al. 2019). These rivers have an essential role in the irrigation of this region for growing crops and fodder (Bharti et al. 2017a, b). However, due to poor soil quality, limited water availability, fodder scarcity, and extreme climate, agro-animal practices are traditional and have low productivity (Acharya et al. 2011; Charan et al. 2013; Bharti et al. 2017a, b; Kumar et al. 2021). Therefore, the region's agriculture sector should be significantly and substantially developed with greater efforts on the production scale. Recent studies on the water quality of Himalayan rivers have indicated the presence of some heavy metals, altered physicochemical properties, high sodium (Na), magnesium (Mg), calcium (Ca), aluminum (Al) level, and the presence of *Escherichia coli* (*E. coli*) (Charan, 2013; Bharti et al., 2017a, b; Giri 2019; Giri et al. 2020). Jeelani et al. (2011) reported mineral sources of surface and spring water in the Kashmir Valley (UT Jammu and Kashmir, India), a north-western Himalaya region, India, due to weathering, rock–water interaction, and anthropogenic activity are the contributing factors to water chemistry. In another study, Mir and Jeelani (2015) found that Jhelum river water (UT Jammu and Kashmir, India) was of good to excellent quality for irrigation purposes. Similarly, Seth et al. (2016) observed that most of the water of the Himalayan rivers of the Kumaun region, Uttarakhand, India, is suitable for irrigation purposes. Haritash et al. (2016) reported that the Ganga water in Rishikesh, India, was alkaline in nature, and the quality ranged from good to excellent for irrigation purposes. Similarly, Sharma and Kumar (2017) found good water quality of Lake Satopanth's in the Garhwal Himalaya, India. These studies revealed that the water quality of different lakes, springs, snowmelt drain, and river of the Garhwal Himalaya, Eastern Himalaya, and North West Himalaya are mainly characterized by carbonate-dominated and carbonate weathering processes. The oxidation–reduction processes release the minerals and heavy metals, while land use/land cover controls the water quality, rock weathering, carbonate, and silicate minerals' weathering processes; these changes are further associated with anthropogenic activity (Kumar et al. 2019; Lone et al. 2020; Rather and Dar 2020; Tiwari et al. 2021; Mir et al. 2021; Kaushik et al. 2021; Das et al. 2022). One study by Tiwari et al. (2021) reported that Indus water quality is affected by anthropogenic activity and carbonate and silicate weathering. These could be due to unique rock–soil–water interaction, high loads of the dynamic population in terms of tourists, inadequate sanitation practices, etc., which might have influenced the water quality. So, water quality deteriorates due to high anthropogenic activity in these high-altitude and mountain regions, although this water could be suitable for irrigation (Thakur et al. 2018; Sharma and Tiwari 2018; Vishwakarma et al. 2018).

However, not much research has been carried out on the hydrochemical and quality assessment of irrigation water in the trans-Himalayan high-altitude region of Leh, Ladakh, India. One of our recent studies indicated that wheat, cabbage, and spinach grown in this Trans Himalayan region have ample trace minerals (Giri et al. 2021a). So, it might be due to irrigation water quality in this region. Therefore, in these enigmas, the present study would enlighten on the irrigation water chemistry and hydrochemical interaction in this high-altitude region of Leh, Ladakh, India. This study's findings may provide the scientific basis for the up-gradation of irrigation systems and agricultural water management in this high-altitude region of India and other similar high-altitude areas of the world.

Study area

The present study was conducted in UT Ladakh, India, a high-altitude region of the north-western Himalayas. The net agricultural sown and the forest is covering approx. 10,196 hectares and 2900 ha, respectively (Anonymous 2009). About 29 sq km of land is being used as cultivated land, 7073 sq km is non-cultivated land, 27,169 sq km is barren cultivable land, and 29 sq km is forest land. Furthermore, insufficient rainfall (0.0–8.0 mm in 2015), extreme climate, and summer and winter temperatures ranging between 33 and − 28 °C make agricultural and animal husbandry practices more difficult. The native people considerably depend upon the rearing of Ladakhi cattle, Changthangi goats and sheep, Ladakhi Yaks for milk, exotic poultry for eggs and meat, and animal husbandry-based livelihood. A total of about 595 no. medium-sized to small industrial units are present here.

The entire Leh gets water from the Indus River and glaciers streams, whereas ponds are significantly less in number. The water drainage system is characteristic of a small Nala/nullah and narrow canal system, carrying river water, snow, and melted glacial water. Other irrigation water sources are spring water and tube well. Local people cultivate wheat, barley, millets, and pulses as the primary food crops, whereas Lucerne is grown for fodder (Bharti et al. 2017a, b). The Canal system plays a vital role in irrigating agricultural fields in this region. Hand pumps and bore wells are the primary sources of drinking water.

Here, the soil is mainly of sandy (80.73%) in nature, followed by silt (12.83%) and clay (6.44%) (Charan et al. 2013; Giri et al. 2019). The nature of rocks is mainly igneous, metamorphic, and sedimentary type. Therefore, there is a need to investigate irrigation water's hydrochemical and water quality in this region for water management for agricultural and other applications.

Materials and methods

Water sample collection and physicochemical and minerals analysis

A total of 500 mL of seventy irrigation water samples were collected from the seven villages, ten samples from each village (Table 1; Fig. 1). The latitude, longitude, and altitude of all the water sampling sites were taken by Garmin GPS 72H and are presented in Table 1. The sampling map is illustrated in Fig. 1. Irrigation water was collected in polypropylene bottles (Tarson Pvt. Ltd.) from the irrigation Nala (or canal) in August 2015.

The temperature, pH, electrical conductivity (EC), total dissolved solids (TDS), and salinity were measured immediately using a HACH ion-selective instrumental method (American Public Health Association 1998). However, anions, viz. chloride (Cl^-), carbonate (CO_3), bicarbonate (HCO_3^-), sulfate (SO_4^{2-}), nitrate (NO_3^-), and phosphate (PO_4^{2-}), were determined later as per the

Table 1 Sampling location (seven different villages) of irrigation water from cold desert high-altitude microclimate

Sampling location	ID of locations	Latitude	Longitude	Altitude (m. AMSL)	Distance from the main city (km)
Ranbirpur	S-1	34°01′40.49"N	77°40′45.89"E	3270	38
Thiksay	S-2	34°02′32.68"N	77°40′19.51"E	3263	31
Chochot	S-3	34°03.957'N	77°37.081'E	3295	25
Shay	S-4	34°04′23.67"N	77°38′21.27"E	3254	30
Choglamsar	S-5	34°06.595'N	77°34.930'E	3235	15
Spituk	S-6	34°06′55.06"N	77°33′16.75"E	3204	10
Nimu	S-7	34°14.27'N	77°29.673'E	3721	45

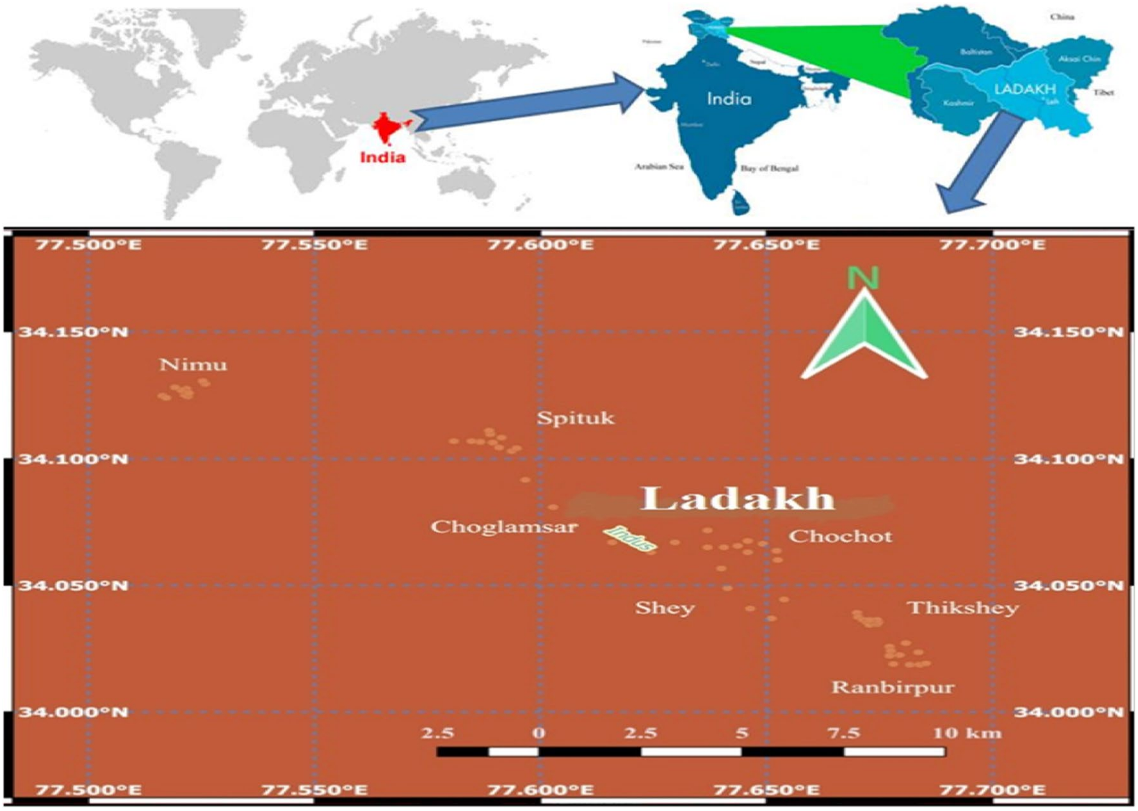


Fig. 1 Sample collection sites made by QGIS software (Adapted from Giri et al. 2019)

standard methods as described in Table 2. Water samples were acid digested for analysis of minerals, viz. Ca, Mg, Na, K, and Si, using inductively coupled plasma optical emission spectroscopy (ICP-OES) (PerkinElmer Analyst, Optima 7000 DV) as per the method described by Giri et al. (2019). The plasma conditions of ICP-OES were as follows: The plasma flow rate was 15 Lt/min, the auxiliary gas flow rate was 0.2 Lt/min, the nebulizer gas flow was 0.8 Lt/min, the RF power was 1300 watts, and the pump flow rate was 1.5 mL/min. (Giri et al. 2021b, a). The limit of detection was investigated using Kicinska's (2018) formula. After subtracting a signal of any contamination from the blank, the solution was examined, and a correction was performed (Giri et al. 2021a).

Analysis of water quality indices of irrigation water

The suitability of irrigation water was determined by evaluating the water quality parameters, viz., total hardness (TH), residual sodium carbonate (RSC), potential salinity (PS), permeability index (PI), Kelly's ratio (KR), magnesium hazard (MH), sodium percentage (Na%), sodium absorption ratio (SAR), corrosivity ratio (CR), and chloroalkaline indices (CAI), using a standard formula as described in Table 3. The classification used in this study for irrigation water suitability is presented in Table 4, which is based on different water quality parameters measured by various authors. The units of the respective parameters were converted into milliequivalents per liter (meq/L).

Classification of irrigation water quality

AquaChem 2014.2, produced by Waterloo Hydrogeologic (2015), was used to classify irrigation water quality graphically. A broad range of hydrochemical computations, statistical summaries, and plots was made available for analysis using this model. Further, Piper, Wilcox, USSL salinity, and Durov's diagrams were also made to determine the suitability of irrigation water for agricultural purposes, as described by Nag and Suchetana (2015) and Singh et al. (2020).

Statistical analysis

The squared Euclidean distance between normalized data was used to measure the similarity between samples or in hierarchical cluster analysis (CA). The dendrogram was obtained after the data was normalized by Ward's method (Giri et al. 2019). All other data analysis was done using Microsoft Office Excel 2007 and the Statistical Package for Social Sciences (SPSS) version 22.

Results and discussion

Physicochemical characteristics of the irrigation water

Mineral uptake by plants mainly depends upon the irrigation water's pH and electrical conductivity (EC) level. More alkaline water types hinder the mineral uptake by plants (Hsieh and Waters 2016). In this study, pH levels in all the

Table 2 Physicochemical and minerals parameters and their analytical techniques are undertaken (Adapted from (Giri et al. 2019)

Sl. No	Parameter	Abbreviation	Unit	Method/Equipment used	Reference
1.	Temperature	TEMP	^{0}C	HACH Instrumental method	(American Public Health Association 1998)
2.	pH	pH	–	HACH Ion-selective instrumental method	(American Public Health Association 1998)
3.	Electrical Conductivity	EC	µS/cm	HACH Ion-selective instrumental method	(American Public Health Association 1998)
4.	Total Dissolved Solids	TDS	mg/L	HACH Ion-selective instrumental method	(American Public Health Association 1998)
5.	Chloride	Cl^-	mg/L	Mohr's Method	(American Public Health Association 2012)
6.	Carbonate & Bicarbonate	CO_3^-, HCO_3^-	mg/L	Titrimetric method	(Singh et al. 2005)
7.	Sulfate	SO_4^-	mg/L	UV–visible spectrophotometric method	(American Public Health Association 2012)
8.	Nitrate	NO_3^-	mg/L	UV–visible spectrophotometric method	(American Public Health Association 2012)
9.	Phosphate	PO_4^-	mg/L	UV–visible spectrophotometric method	(American Public Health Association 2012)
10.	Minerals	Ca, Mg, Na, K, Si	mg/L	ICP-OES Instrumental method	(Giri et al. 2019)

Ca calcium, *Mg* magnesium, *Na* sodium, *K* potassium, *Si* silica

Table 3 Different indices/parameters used for evaluation of water quality

Sl. No	Index	Symbol	Unit	Equation	Source
1.	Total Hardness	TH	mg/L	$\mathbf{TH = (2.5 \times Ca^{2+}) + (4.2 \times Mg^{2+})}$	(Todd and Mays 2005)
2.	Residual Sodium Carbonate	RSC	meq/L	$\mathbf{RSC = ({CO_3}^{2-} + {HCO_3}^{-}) – (Ca^{2+} + Mg^{2+})}$	(Eaton et al. 1995)
3.	Potential Salinity	PS	meq/L	$\mathbf{PS = Cl^{-} + (0.5 \times {SO_4}^{2-})}$	(Doneen 1964)
4.	Permeability Index	PI	%	$\mathrm{PI} = \frac{\mathrm{Na^{+}} + \sqrt{\mathrm{HCO_3^-}}}{\mathrm{Ca^{2+} + Mg^{2+} + Na^{+}}} \times 100$	(Doneen 1964)
5.	Kelly's Ratio	KR	meq/L	$\mathrm{KR} = \frac{\mathrm{NA^{+}}}{\mathrm{Ca^{2+} + Mg^{2+}}}$	(Kelley 1963)
6.	Magnesium Hazard	MH	%	$\mathrm{MH} = \frac{\mathrm{Mg^{+}}}{\mathrm{Ca^{2+} + Mg^{2+}}} \times 100$	(Szabolcs 1964)
7.	Sodium Percentage	Na %	%	$\mathrm{NA\%} = \frac{\mathrm{Na^{+} + K^{+}}}{\mathrm{Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}}} \times 100$	(Todd and Mays 2005)
8.	Sodium Absorption Ratio	SAR	meq/L	$\mathrm{SAR} = \frac{\mathrm{NA^{+}}}{\sqrt{\mathrm{Ca^{2+}}} + \mathrm{Mg^{2+}})/2}$	(Allison 1964)
9.	Corrosivity Ratio	CR	mg/L	$\mathrm{CR} = \frac{(\mathrm{Cl^{-}}/35) + 2(\mathrm{SO_4^{2-}}/96)}{(\mathrm{CO_3^{2-}} + \mathrm{HCO_3^{-}}/100}$	(Balasubramanian 1986)
10.	Chloroalkaline indices 1	CAI1	meq/L	$\mathrm{CAI1} = \frac{\mathrm{Cl^{-}} \text{ - } (\mathrm{Na^{+} + K^{+}})}{\mathrm{Cl^{-}}}$	(Schoeller 1977)
11.	Chloroalkaline indices 2	CAI2	meq/L	$\mathrm{CAl2} = \frac{\mathrm{Cl^{-}} \text{ - } (\mathrm{Na^{+} + K^{+}})}{\mathrm{SO_4^{2-} + CO_3^{-} + NO_3^{-}}}$	(Schoeller 1977)

Table 4 Classification of irrigation water suitability based on Na%, SAR, MH, KR RSC, and TDS (Kelley 1940; Wilcox 1948; Thorne 1954; Todd and Mays 1980; United States Environmental Protection Agency 1986)

Sl. No	Index	Class											
		Exc	Go	Perm	Dou	Su	UnSu	REP	DEP	Soft	Mode	Hard	V. Hard
1.	pH	–	6.5–8.4	–	–	–	–	–	–	–	–	–	–
2.	EC	< 250	250–750	750–2250	–	–	–	–	–	–	–	–	–
3.	TDS	< 450	450–2000	–	–	–	> 2000	–	–	–	–	–	–
4.	TH	–	–	–	–	–	–	–	–	0–60	60–120	120–180	> 180
5.	RSC/RA	–	< 1.25	–	1.25–2.5	–	> 2.5	–	–	–	–	–	–
6.	PS	–	–	–	–	< 3	> 3	–	–	–	–	–	–
7.	PI	–	25–75%	–	–	> 75%	< 25%	–	–	–	–	–	–
8.	KR/KI	–	–	–	–	< 1	> 1	–	–	–	–	–	–
9.	MAR/MH	–	–		–	< 50	> 50	–	–	–	–	–	–
10.	%Na	< 20	20–40	40–60	60–80	–	> 80	–	–	–	–	–	–
11.	SAR	< 10	10–18	–	18–26	–	> 26	–	–	–	–	–	–
12.	CR	–	–	–	–	< 1	> 1	–	–	–	–	–	–
13.	CAI1	–	–	–	–	–	–	– tiv	+ tiv	–	–	–	–
14.	CAI2	–	–	–	–	–	–	– tiv	+ tiv	–	–	–	–

Exc. excellent, *Go.* good, *Perm.* permeable, *Dou.* doubtful, *Su*unsuitable, *REP* reverse exchange process, *DEP* direct exchange process, V. *Hard* very hard, *TH* total hardness, *PS* potential salinity, *Na %* sodium percentage, *MH* magnesium hazard, *RSC* residual sodium carbonate, *PI* permeability index, *KR*-Kelly's ratio, *SAR* sodium absorption ratio, *PAR* potassium absorption ratio, *SSP* soluble sodium percentage, *CROSS* cation ratio of structural stability, *CAI1* chloroalkaline indices 1, *CAI2* chloroalkaline indices 2, *CR* corrosivity ratio, – *tiv*. negative, + *tiv*. positive

sampling locations were alkaline in nature. The increasing pattern of pH of all the sampling locations were 8.04 ± 0.09(S-6) < 8.14 ± 0.03(S-4) < 8.29 ± 0.04(S-5) < 8.34 ± 0.08(S-3) < 8.40 ± 0.07(S-2) < 8.53 ± 0.04(S-1) < 8.66 ± 0.10(S-7) (Table 5; Fig. 2A). These higher and lower pH levels varied at different locations. It was found that sampling locations 6 (S-6) and 7 (S-7) have the lowest and highest pH values, respectively. The normal range of irrigation water pH levels is 6.5–8.4 (Ayers and Wescott 1985; World Health Organization 2006). Therefore, S-1 and S-7 have slightly higher pH levels than the permissible limit. This might be due to the slightly higher interaction of minerals, organic carbon decomposition, and untreated waste disposal prevalent in these two study areas (Nduka and Orisakwe 2011; Tiwari et al. 2017). Our earlier findings showed that the groundwater (7.70 ± 0.04) and surface water (8.36 ± 0.01) was alkaline in nature (Bharti 2017; Giri et al. 2017, 2019, 2020). This could be due to the alkaline nature of the soil in this region (Charan et al. 2013).

Table 5 General descriptive statistics of physicochemical and minerals (mg/L) level in irrigation water from high altitude

Location	Attributes	pH	EC	TDS	Cl^-	SO_4^-	PO_4^-	CO_3^-	HCO_3^-	NO_3^-	Ca	Mg	Na	K	Si
S-1 (Ranbirpur)	Mean	8.53±0.04	312.80±1.15	152.56±1.48	27.59±1.93	6.20±0.36	0.44±0.09	0.00±0.00	27.89±1.25	0.03±0.01	32.12±2.33	8.77±0.92	0.41±0.10	0.41±0.09	4.78±0.43
	Minimum	8.23	308.00	147.00	21.02	4.00	0.05	0.00	20.56	0.01	19.94	2.97	0.10	0.14	3.61
	Maximum	8.69	318.00	160.40	39.24	8.00	0.80	0.00	32.92	0.06	42.91	13.45	0.95	1.06	8.02
S-2 (Thiksay)	Mean	8.40±0.07	317.40±2.55	152.65±2.06	18.68±1.68	6.40±0.37	0.53±0.12	1.16±0.38	26.76±0.27	0.03±0.00	40.89±4.26	11.04±0.69	0.90±0.31	0.71±0.23	5.44±0.62
	Minimum	7.85	309	143.80	12.61	5.00	0.06	0.00	25.52	0.01	30.71	8.86	0.27	0.28	3.96
	Maximum	8.67	333.00	166.20	26.23	8.00	1.10	3.16	27.96	0.06	76.99	16.79	3.15	2.51	9.94
S-3 (Chochot)	Mean	8.34±0.08	324.60±5.13	151.40±0.90	23.31±1.98	7.70±0.30	0.07±0.01	0.00±0.00	26.53±0.53	0.04±0.00	34.52±4.97	9.36±1.22	0.70±0.20	0.58±0.13	5.17±0.53
	Minimum	8.30	310	146.20	16.82	6.00	0.02	0.00	24.12	0.01	19.94	2.97	0.10	0.14	3.61
	Maximum	8.38	362.00	156.40	30.83	9.00	0.09	0.00	28.52	0.06	76.99	16.79	1.98	1.32	8.02
S-4 (Shay)	Mean	8.14±0.03	335.20±12.56	160.82±9.82	27.95±1.15	7.60±0.65	1.10±0.21	0.00±0.00	32.02±1.73	0.03±0.00	38.11±4.53	10.67±0.75	0.87±0.32	0.68±0.24	5.21±0.66
	Minimum	8.02	317	84.30	23.03	4.00	0.04	0.00	24.60	0.01	28.10	8.52	0.10	0.14	3.61
	Maximum	8.39	447.00	193.40	33.24	11.00	1.80	0.00	40.48	0.04	76.99	16.79	3.15	2.51	9.94
S-5 (Choglamsar)	Mean	8.29±0.04	368.9±8.59	161.77±6.27	14.29±1.38	4.90±0.53	0.45±0.20	1.05±0.48	32.95±1.54	0.02±0.00	33.34±2.36	9.00±0.95	0.44±0.09	0.43±0.08	4.86±0.41
	Minimum	8.03	324	149.20	10.81	3.00	0.03	0.00	23.54	0.01	19.94	2.97	0.12	0.16	3.68
	Maximum	8.46	401.00	216.20	24.63	8.00	1.60	4.28	38.08	0.04	42.91	13.45	0.95	1.06	8.02
S-6 (Spituk)	Mean	8.04±0.09	394.8±6.12	193.35±3.83	22.50±2.48	5.90±0.31	3.67±1.78	0.17±0.17	35.02±0.26	0.02±0.00	37.02±4.64	10.49±0.77	0.91±0.32	0.72±0.23	5.31±0.65
	Minimum	7.48	374.00	180.40	11.21	4.00	0.07	0.00	33.26	0.01	27.65	8.44	0.10	0.14	3.61
	Maximum	8.29	421.00	210.50	31.63	7.00	16.00	1.68	35.84	0.04	76.99	16.79	3.15	2.51	9.94
S-7 (Nimu)	Mean	8.66±0.10	164.84±21.51	78.01±10.29	24.87±1.86	6.40±0.31	0.66±0.28	0.00±0.00	18.87±2.52	0.02±0.00	35.39±2.36	9.31±0.97	0.41±0.09	0.41±0.08	4.80±0.41
	Minimum	7.84	121.70	56.30	16.22	5.00	0.01	0.00	11.96	0.01	19.94	2.97	0.12	0.16	3.68
	Maximum	8.97	272.00	130.80	34.24	8.00	3.00	0.00	36.96	0.03	42.91	13.45	0.95	1.06	8.02

EC electrical conductivity, *TDS* total dissolved solids, Cl^- chloride, SO_4^- sulfate, PO_4^- phosphate, CO_3^- carbonate, $HCO_3.^-$ bicarbonate, Ca calcium, *Mg* magnesium, *Na* sodium, *K* potassium, *Si* silica

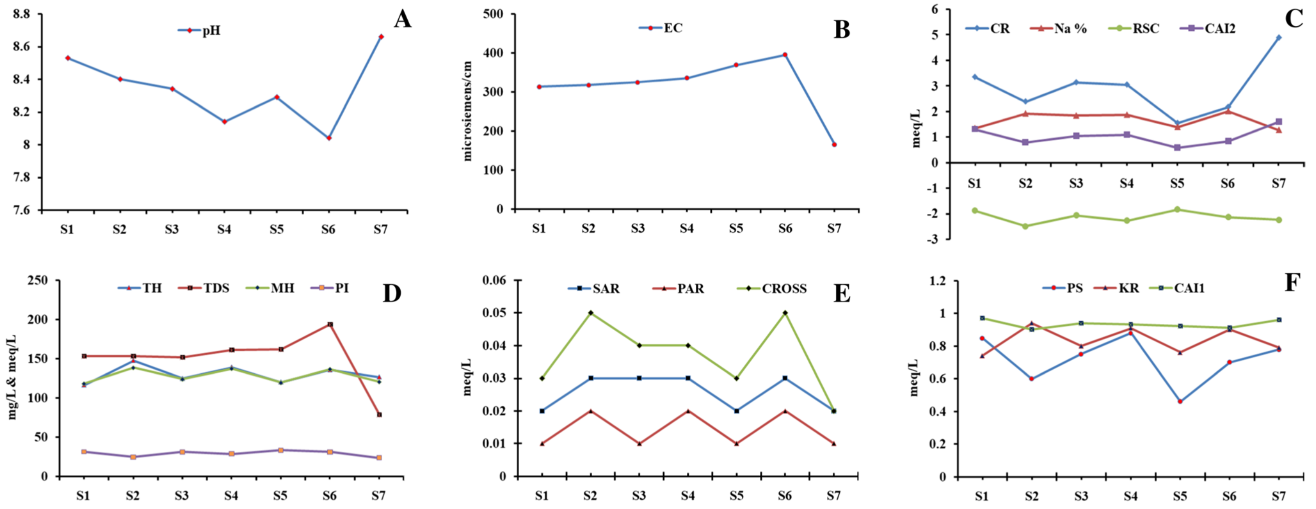


Fig. 2 **A–F** Graphical representation of different irrigation water indexes of different sites from high altitude (Leh, Ladakh, India). *EC* Electrical Conductivity' *TDS* Total Dissolved Solids, *TH* Total Hardness, *PS* Potential Salinity, *Na%* Sodium Percentage. *MH* Magnesium Hazard; *RSC* Residual Sodium Carbonate, *PI* Permeability Index; *KR* Kelly's Ratio, *SAR* Sodium Absorption Ratio; *PAR* Potassium AbsorptionRatio, SSP-Soluble Sodium Percentage; CAI1-Chloroalkaline indices 1, *CAI2* Chloroalkaline indices 2; *CR* Corrosivity Ratio

Therefore, soil health and water quality management at S-1 and S-7 should be introduced to reduce the pH for better mineral uptake by plants.

Electrical conductivity (EC) depends upon the presence of salt in the water and is an important parameter of irrigation water. The excess EC of irrigation water may affect the crop yield since growth stage varies with the mineral uptake from soil (Ayers and Wescott 1985; Bauder and Brock 2001). In this study, the EC level of all the locations fall [164.84 ± 21.51(S-7) < 312.80 ± 1.15(S-1) < 317.40 ± 2.55(S-2) < 324.60 ± 5.13(S-3) < 335.20 ± 12.56(S-4) < 368.90 ± 8.59(S-5) < 394.80 ± 6.12(S-6) µS/cm] within the normal limit (750 µS/cm) as per WHO standard (World Health Organization 2006) (Table 5; Fig. 2B). However, irrigation water classified as excellent has an EC of 250 µS/cm, 250–750 µS/cm for good, although 750–2250 µS/cm is permissible if proper management is provided (Ayers and Wescott 1985) (Table 4). Therefore, the present findings showed that water quality in respect of EC was in the good category across all the sampling locations. Furthermore, this study corroborates the findings of Acharya et al. (2011) and Charan (2013), who reported that the EC level was not exceeding the normal range. Our earlier results reported that the EC level in groundwater (448.74 ± 19.77 µS/cm) and surface water (336.43 ± 3.64 µS/cm) was within the limit and suitable for agricultural purposes (Charan 2013; Giri et al. 2017, 2019, 2020).

Another major factor affecting water quality in the agriculture field is total dissolved solids (TDS), which depend upon minerals and ions like Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, CO_3^{-}, HCO_3^{-}, Cl^{-}, SO_4^{2-}, and PO_4^{3-}. The natural sources of all these constituents are the weathering process of rock, the ion exchange process between soil–water and anthropogenic activity (Sheikhy Narany et al. 2014; Talib et al. 2019; Saha et al. 2019). The evaporation caused the accumulation of these minerals and their ions in the water and played an important factor in soil nutrient uptake (Modi 2008; Singh et al. 2013). The classification of water quality based on TDS is as follows: excellent for irrigation at < 450 mg/L, good within 450–2000 mg/L, and unsuitable > 2000 mg/L (Skoet et al. 2006) (Table 4). In this study, the TDS level of all the locations were 78.01 ± 10.29 (S-7) < 151.40 ± 0.90 (S-3) < 152.56 ± 1.48 (S-1) < 152.65 ± 2.06 (S-2) < 160.82 ± 9.82 (S-4) < 161.77 ± 6.27 (S-5) < 193.35 ± 3.83 (S-6) mg/L (Table 5; Fig. 2D). These findings are indicative of the good quality of irrigation water. Earlier studies also found that the TDS levels of groundwater and surface water were 238.50 ± 9.87 mg/L and 155.41 ± 1.09 mg/L, respectively (Giri et al. 2017, 2019). Therefore, there was nothing concerning using irrigation water from the studied locations for agricultural purposes.

The range of chloride, sulfate, phosphate, carbonate, bicarbonate, and nitrate in all the sampling location were 14.29 ± 1.38––27.95 ± 1.15 mg/L, 4.90 ± 0.53–7.70 ± 0.30 mg/L, 0.07 ± 0.01–3.67 ± 1.78 mg/L, 0.00 ± 0.00–1.16 ± 0.38 mg/L, 18.87 ± 2.52–35.02 ± 0.26 mg/L, 0.02 ± 0.00–0.04 ± 0.00 mg/L, respectively (Table 5). The order of all these anions are as nitrate < carbonate < phosphate < sulfate < chloride < bicarbonate. For irrigation purposes, the permissible limits of Cl^{-}, SO_4^{2-}, HCO_3^{-}, and NO_3^{-} are 250 mg/L, 200 mg/L, 200 mg/L, and 50 mg/L, respectively. These data revealed that studied irrigation water contains a permissible level of various salt ions as per the standard of the World Health Organization (World Health Organization 2006).

The Ca^{2+}, Mg^{2+}, Na^+ and Si range are 32.12 ± 2.33–40.89 ± 4.26 mg/L, 9.36 ± 1.22–10.49 ± 0.77 mg/L, 0.41 ± 0.09–0.91 ± 0.32 mg/L, 0.41 ± 0.08–0.72 ± 0.23 mg/L, 4.78 ± 0.43–5.44 ± 0.62 mg/L, respectively (Table 5). The order of all these minerals are K < Na < Si < Mg < Ca. For irrigation purposes, the permissible limits of Ca^{2+}, Mg^{2+}, and Na^+ are 75 mg/L, 30 mg/L, and 200 mg/L, respectively (Singh et al. 2020). Therefore, all the mineral levels in the present study are within the normal range. However, a higher level of Ca^{2+} and Mg^{2+} may cause mineral interaction and inhibit Na^+ uptake by plants. The presence of Cl^- and HCO_3^- ions in irrigation water are critical for plant growth. These two ions control the salinity, SAR level, and adsorption of Ca^{2+} and Mg^{2+}. Further, higher Ca^{2+} and Mg^{2+} levels also affect plants' iron uptake (Hughes and Hanan 1977; Agarwala and Mehrotra 1978; Sonneveld 1979; Garg et al. 1980). The present study findings are corroborated by the findings of Charan (2013) and Charan et al. (2013), who reported lower levels of Fe in plants and a relatively higher level of Ca^{2+}, Mg^{2+}, Cl^-, and HCO_3^- in irrigation water. This might be due to the rock and irrigation water interaction. Since the lithology of this study area is predominantly of silicate and dolomite types. This condition will favor cation–anion exchange between irrigation water and host lithology, or vice versa (Hughes and Hanan 1977; Agarwala and Mehrotra 1978; Sonneveld 1979; Garg et al. 1980). There are two types of cation–anion exchange processes, viz. direct and inverse. In the case of the direct exchange process, the Na^+ and K^+ levels of water will be exchanged with Ca^{2+} and Mg^{2+} of the host rock, whereas Ca^{2+} and Mg^{2+} of water will be exchanged with Na^+ and K^+ of the host rock in the inverse ion exchange process (Schoeller 1977).

The suitability of water for irrigation

In this study, water quality index parameters, viz. PS, Na%, RSC, PI, KR, SAR, SSP, CAI1, CAI2, and CR, were calculated to determine the suitability of water for irrigation purposes. The total hardness of water results from the total calcium (Ca^{2+}) and magnesium (Mg^{2+}) concentrations in the water. The United States Environmental Protection Agency (USEPA) (1986) categorizes water as soft (0–60 mg/L), moderately hard (60–120 mg/L), hard (120–180 mg/L), or very hard (> 180 mg/L) (Table 4). The present study observed an increasing pattern of total hardness (TH) (mg/L) at all the sampling sites (SS), viz. S-3 (124.67 ± 16.80). These findings indicated that all locations fell into the moderately hard to hard category. Our earlier studies reported that groundwater (235.99 ± 13.87 mg/L) and surface water (187.27 ± 5.65 mg/L) were within the hard to very hard category (Giri et al. 2017, 2019). This might be due to natural and anthropogenic activity. This caused carbonate ($CaCO_3$) and dolomite (CaMg $(CO_3)_2$ formation in the form of chalk and limestone in the soil. Earlier studies have reported that the soil in this region is alkaline and enriched with higher Ca^{2+} and Mg^{2+} levels. Therefore, all these factors caused the higher hardness level in irrigation water, which is detrimental to fodder and vegetable crops, as a higher level of hardness inhibits plant growth (Singh et al. 2013). Therefore, all the water sources in these areas must be appropriately managed to reduce the water hardness for sustainable agriculture practices in this high-altitude region.

Potential salinity (PS) is a Cl^- and SO_4^{2-}-based parameter index for categorizing irrigation water for agricultural use. An earlier study found that the < 3 meq/L PS level is suitable for irrigation purposes, whereas it is unsuitable at the > 3 meq/L (Doneen 1964) (Table 4). In this study, the PS level of all the locations was 0.46 ± 0.04 (S-5) < 0.60 ± 0.05 (S-2) < 0.70 ± 0.07 (S-6) < 0.75 ± 0.05 (S-3) < 0.78 ± 0.05 (S-7) < 0.85 ± 0.06 (S-1) < 0.88 ± 0.03 (S-4) meq/L, which is less than 3 meq/L (Table 6; Fig. 2F). This could be due to the lower Cl^- and SO_4^2 levels in all the water samples. These findings indicate that water is suitable for irrigation purposes in this study area.

Permeability index (PI) is the parameter-based index to determine the capability of water to move (permeability) through the soil. The concentration of Na^+, Ca^{2+}, Mg^{2+}, and HCO_3^- in water determines the soil profile in terms of soil porosity (Singh et al. 2015). Depending upon the PI level, water is classified as Class I, Class II, and Class III types. Class I and II waters are categorized as good for irrigation with 75% or more maximum permeability, whereas Class III water is unsuitable, with 25% maximum permeability (Doneen 1964) (Table 4). In the present study, the PI of all the locations were 23.42 ± 2.53 (S-7) < 24.49 ± 1.55 (S-2) < 28.36 ± 1.95 (S-4) < 30.69 ± 3.43 (S-3) < 30.73 ± 2.02 (S-6) < 31.17 ± 2.79 (S-1) < 33.06 ± 3.65 (S-5) % (Table 6; Fig. 2D). These findings indicate that water comes into the class III category and is unsuitable for irrigation. One study from Doon Valley in the outer Himalayas (Uttarakhand, India) reported that irrigation water quality in the PI level was suitable except at some sites. The study concluded that there might be higher Na^+, Ca^{2+}, Mg^{2+}, and HCO_3^- at those sites (Dudeja et al. 2011).

Kelly's ratio (KR) is another important water quality parameter that reveals the level of Na^+ against Ca^{2+} and Mg^{2+} ion concentrations in the water. KR value < 1 is suitable for irrigation, but KR value > 1 is unsuitable (presence of excess Na^+) (Kelley 1963) (Table 4). In the present study, the KR level of all the locations was 0.74 ± 0.08 (S-1) < 0.76 ± 0.08 (S-5) < 0.79 ± 0.08 (S-7) < 0.80 ± 0.10 (S-3) < 0.90 ± 0.07 (S-6) < 0.91 ± 0.06 (S-4) < 0.94 ± 0.06

Table 6 Different water quality indices estimated in irrigation water collected from high altitude

Location	Attributes	TH	RSC	PS	PI	KR	MH	Na %	SAR	CR	CAI1	CAI2
S-1 (Ranbirpur)	Mean ± SEM	116.25 ± 9.04	−1.88 ± 0.18	0.85 ± 0.06	31.17 ± 2.79	0.74 ± 0.08	118.07 ± 10.65	1.35 ± 0.45	0.02 ± 0.00	3.35 ± 0.26	0.97 ± 0.01	1.31 ± 0.09
	Minimum	62.04	−2.57	0.66	22.26	0.29	49.61	0.35	0.00	2.23	0.93	0.90
	Maximum	154.57	−0.84	1.19	52.40	1.14	168.45	5.15	0.05	4.65	0.99	1.80
S−2 (Thiksay)	Mean ± SEM	147.47 ± 13.36	−2.49 ± 0.27	0.60 ± 0.05	24.49 ± 1.55	0.94 ± 0.06	138.28 ± 4.92	1.92 ± 0.68	0.03 ± 0.01	2.39 ± 0.19	0.90 ± 0.03	0.78 ± 0.06
	Minimum	113.11	−4.78	0.41	13.77	0.75	121.95	0.67	0.01	1.70	0.72	0.55
	Maximum	261.31	−1.83	0.83	29.75	1.42	176.26	6.99	0.12	3.29	0.96	1.12
S−3 (Chochot)	Mean ± SEM	124.67 ± 16.80	−2.07 ± 0.34	0.75 ± 0.05	30.69 ± 3.43	0.80 ± 0.10	123.72 ± 12.25	1.84 ± 0.53	0.03 ± 0.01	3.14 ± 0.24	0.94 ± 0.02	1.05 ± 0.10
	Minimum	62.04	−4.85	0.56	13.09	0.29	49.61	0.35	0.00	2.39	0.83	0.74
	Maximum	261.31	−0.78	0.96	55.98	1.42	176.26	5.15	0.08	4.29	0.98	1.45
S-4 (Shay)	Mean ± SEM	139.01 ± 14.32	−2.27 ± 0.28	0.88 ± 0.03	28.36 ± 1.95	0.91 ± 0.06	137.14 ± 5.19	1.87 ± 0.69	0.03 ± 0.01	3.05 ± 0.16	0.93 ± 0.03	1.10 ± 0.07
	Minimum	105.17	−4.59	0.74	16.58	0.72	121.48	0.35	0.00	2.33	0.72	0.86
	Maximum	261.31	−1.52	1.03	36.84	1.42	176.26	6.99	0.12	3.67	0.99	1.50
S-5 (Choglamsar)	Mean ± SEM	120.24 ± 9.28	−1.84 ± 0.18	0.46 ± 0.04	33.06 ± 3.65	0.76 ± 0.08	119.31 ± 10.84	1.40 ± 0.44	0.02 ± 0.00	1.55 ± 0.17	0.92 ± 0.02	0.58 ± 0.08
	Minimum	62.04	−2.49	0.36	24.27	0.29	49.61	0.43	0.01	1.13	0.78	0.34
	Maximum	154.57	−0.64	0.75	63.41	1.14	168.45	5.15	0.05	2.76	0.98	1.23
S−6 (Spituk)	Mean ± SEM	135.54 ± 14.67	−2.14 ± 0.30	0.70 ± 0.07	30.73 ± 2.02	0.90 ± 0.07	136.37 ± 5.22	2.01 ± 0.67	0.03 ± 0.01	2.18 ± 0.20	0.91 ± 0.03	0.84 ± 0.10
	Minimum	103.71	−4.70	0.38	15.15	0.71	121.14	0.35	0.00	1.24	0.72	0.40
	Maximum	261.31	−1.51	0.97	36.74	1.42	176.26	6.99	0.12	3.02	0.99	1.23
S-7 (Nimu)	Mean ± SEM	126.64 ± 9.47	−2.24 ± 0.19	0.78 ± 0.05	23.42 ± 2.53	0.79 ± 0.08	120.50 ± 10.93	1.28 ± 0.45	0.02 ± 0.00	4.89 ± 0.42	0.96 ± 0.01	1.60 ± 0.15
	Minimum	62.04	−2.81	0.55	15.13	0.29	49.61	0.43	0.01	2.55	0.91	1.09
	Maximum	154.57	−1.01	1.03	41.01	1.14	168.45	5.15	0.05	6.80	0.99	2.62

S-1 to S-7 Station-1 to Station-7, *TH* total hardness, *PS* potential salinity, *Na%* sodium percentage, *MH* magnesium hazard, *RSC* residual sodium carbonate, PI permeability index, *KR* Kelly's ratio, *SAR* sodium absorption ratio, PAR potassium absorption ratio, *SSP* soluble sodium percentage, *CAI1* chloroalkaline indices 1, *CAI2* chloroalkaline indices 2, *CR* corrosivity ratio

(S-2) meq/L (Table 6; Fig. 2F). This might be due to the dominant levels of Ca^{2+} and Mg^{2+} in all the water samples, and therefore, the water of these areas is appropriate for irrigation purposes (Alharbi 2018).

As shown in Table 4, magnesium hazard (MH) also stands for magnesium adsorption ratio (MAR). Mg^{2+} is the crucial element that determines water quality. Ca^{2+} and Mg^{2+} maintain the cationic equilibrium, but higher Mg^{2+} alters the agriculture yield after releasing Na^+ from the soil. This consequence alters the soil's chemical structure and ultimately affects the crop yield (Ayers and Wescott 1985; Joshi et al. 2009). MH of less than 50% is suitable for irrigation, whereas higher than 50% is unsuitable for irrigation purposes (Ayers and Wescott 1985) (Table 4). The present study found that the MH level of all the locations was 118.07 ± 10.65 (S-1) < 119.31 ± 10.84 (S-5) < 120.50 ± 10.93 (S-7) < 123.72 ± 12.25 (S-3) < 136.37 ± 5.22 (S-6) < 137.14 ± 5.19 (S-4) < 138.28 ± 4.92 (S-2) % (Table 6; Fig. 2D). This might be due to the dominant nature of Mg^{2+} in all the collected samples. These findings are suggestive that water is not suitable for agricultural purposes as this may harm the soil infiltration properties.

In this study, Na% at all the locations was 1.28 ± 0.45 (S-7) < 1.35 ± 0.45 (S-1) < 1.40 ± 0.44 (S-5) < 1.84 ± 0.53 (S-3) < 1.87 ± 0.69 (S-4) < 1.92 ± 0.68 (S-2) < 2.01 ± 0.67 (S-6) % (Table 6; Fig. 2C). The percentage of sodium (Na %) plays a crucial role in classifying water for irrigation purposes (Wilcox 1955). This classification of irrigation water depends upon the Na% and can be divided into five categories: excellent (Na% < 20%), good (20% < Na% < 40%), permissible (40% < Na% < 60%), doubtful (60% < Na% < 80%), and unsuitable (Na% > 80%) (Table 4). A higher Na^+ excess level will cause the soil to become alkaline (Na^+ addition with HCO_3^-) or saline (Na^+ addition with Cl^-). The Na^+ concentration in irrigation water will force the other ions to move into the clay particles after removing the Ca^{2+} and Mg^{2+} by increasing the base exchange process. As a result, all of these will obstruct the smooth percolation of water through the soil. Ultimately, it will reduce the soil permeability and increase the deflocculating process (Kelley 1963; Joshi et al. 2009; Abderamane et al. 2013). Therefore, the irrigation water studied in this study comes within the excellent category for Na%. This might be due to the lower abundance of Na^+ in all the water samples.

The sodium adsorption ratio (SAR) is also related to the Na% in the irrigation water, with a slight difference. The higher level of Na^+ replaces the Ca^{2+} and Mg^{2+}, and the quantity of Na^+ that is getting adsorbed to the soil is called SAR. Higher SAR would cause a higher reduction in water permeability (Eaton et al. 1995; Gholami and Srikantaswamy 2009; Dash et al. 2014). Based on SAR, groundwater can be classified into four categories, viz. excellent (SAR < 10 meq/L), good (10–18 meq/L SAR), doubtful (18–26 meq/L SAR), and unsuitable (SAR > 26 meq/L) (Table 4). In this study, results revealed that the SAR in all the locations was 0.02 ± 0.00 (S-5) < 0.02 ± 0.00 (S-1) < 0.02 ± 0.00 (S-7) < 0.03 ± 0.01 (S-6) < 0.03 ± 0.01 (S-2) < 0.03 ± 0.01 (S-4) < 0.03 ± 0.01 (S-3) meq/L (Table 6; Fig. 2E). Based on the present findings of SAR, all the water samples are suitable for irrigation purposes. Haritash et al. (2016) and Sharma et al. (2014) reported low SAR levels, which supports this finding, an indication that the water samples can be used for irrigation.

The Wilcox (1948) diagram for the USSL salinity diagram (Richards 1954) represents water Na% and EC-based water classification for irrigation application (Fig. 3). The diagram showed that the S-7 sampling site in the C1-S1 has low sodium and salinity hazard (Fig. 3). All the other locations of C2-S1 indicate medium salinity and low Na hazard. This might be due to lower Na^+ levels in most water samples (Table 5). Therefore, all the water samples in the study area are suitable for irrigation purposes.

The comparative study of Ca^{2+}, Mg^{2+} as HCO_3^- and CO_3^- is described as Residual Sodium Carbonate (RSC). A higher level of Ca^{2+} and Mg^{2+} deposition as HCO_3^- and CO_3^- will increase the Na^+ level in the soil. Further, an excess amount of CO_3^- and HCO_3^- to Ca^{2+} and Mg^{2+} may influence the quality of the water for irrigation purposes. The higher surplus amount of CO_3^- and HCO_3^- will mostly interact with Ca^{2+} than Mg^{2+}, and this will cause precipitation. Therefore, this will cause the inverse ion exchange process, which ultimately causes sodium hazards (Zaidi et al. 2015; Haritash et al. 2016; Singh et al. 2020). Thereafter, higher Na^+ causes the dissolution of organic matter and causes a black spot in the dried soil (Pinder 2011). The RSC level of < 1.25 meq/L is classified as good, whereas the 1.25–2.5 meq/L level is doubtful for irrigation purposes (Table 4). Hence, water with an RSC greater than 2.5 meq/L is considered unsuitable for irrigation. In this study, the RSC level in all the locations is 1.84 ± 0.18 (S-5) > -1.88 ± 0.18 (S-1) > -2.07 ± 0.24 (S-3) > -2.14 ± 0.30 (S-6) > -2.24 ± 0.19 (S-7) > -2.27 ± 0.28 (S-4) > -2.49 ± 0.27 (S-2) meq/L (Table 6; Fig. 2C). These findings revealed that the entire location has less RSC. The negative level of RSC might be due to various dissolved inorganic solids, ions, minerals, etc., from domestic waste. Our earlier study has pointed out that improper sanitation and wastage management hamper the groundwater and surface water in this high-altitude region (Giri et al. 2017, 2019). RSC's current findings are similar to the study of Haritash et al. (2016), where they reported a negative RSC level in the Ganga river at Rishikesh, India, another Himalayan mountain region.

The corrosivity ratio (CR) is an important indicator of whether water can be supplied using a metal pipe or note. If the CR value is less than one (< 1), then water may be

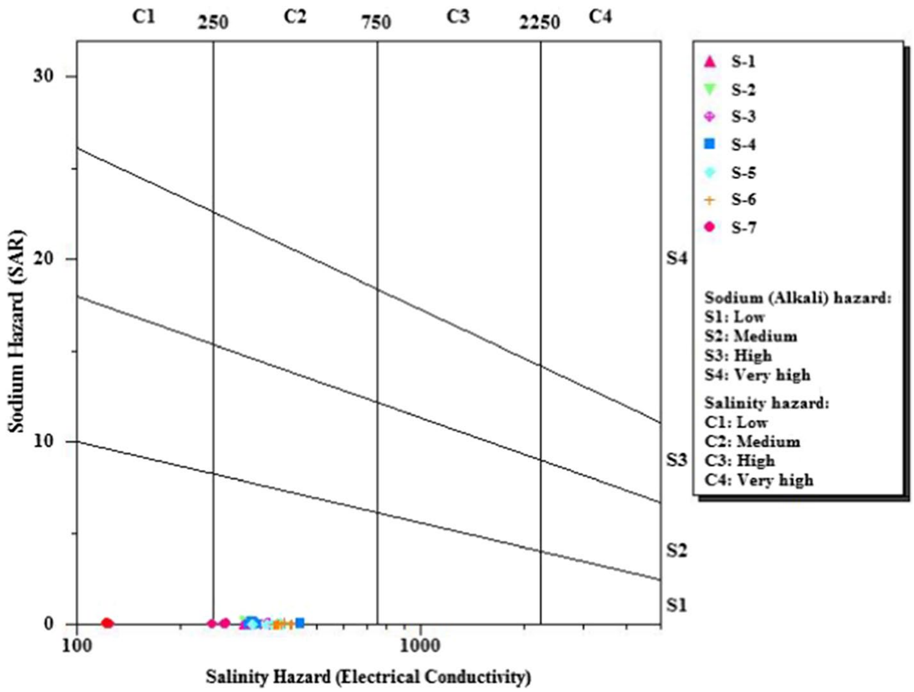


Fig. 3 United States Salinity Laboratory (USSL) diagram (*SAR* Vs. Salinity Hazard) showing the hazard level of sodium and salinity of irrigation water at high altitude (Leh, Ladakh, India) (after Richards, 1954)

supplied through any metal pipe, whereas at greater than one (> 1) CR value, water is not suitable for supply using a metal pipe due to increased corrosion (Balasubramanian 1986; Aravindan et al. 2004; Shankar et al. 2011) (Table 4). The present study showed that the CR level at all the locations was 1.55 ± 0.17 (S-5) < 2.18 ± 0.20 (S-6) < 2.39 ± 0.19 (S-2) < 3.05 ± 0.16 (S-4) < 3.14 ± 0.24 (S-3) < 3.35 ± 0.26 (S-1) < 4.89 ± 0.42 (S-7) mg/L (Table 6; Fig. 2C). These findings are important as the CR value is greater than 1, indicating that irrigation water in this region should not be transported through the metal pipe. This elevated CR might be due to higher Cl^- and SO_4^{2-} levels in irrigation water (Rawat et al. 2018). This finding agrees with many farmers' complaints regarding the damage to the irrigation pipe channel in this study area. Hence, it is suggested that they should use plastic pipes or rust-resistant metal pipes.

Chloroalkaline index (CAI) is attributed to the level of chloride (Cl^-). The chloride ion controls the soil equilibrium and helps in photosynthesis in plants. However, their excess levels alter the soil's chemical structure and cause toxicity to plants. Further, CAI1 and CAI2 determine the presence of ion exchange between the rock and water. The positive CAI indicates the occurrence of the direct exchange process between Na^+ and K^+ in water with Mg^{2+} and Ca^{2+} in rocks. However, the negative value indicates the reverse exchange process (Jafar Ahamed et al. 2013; Kumar et al. 2014; Salifu et al. 2017) (Table 4). In this study, CAI1 and CAI2 were 0.90 ± 0.03 (S-2) < 0.91 ± 0.03 (S-6) < 0.92 ± 0.02 (S-5) < 0.93 ± 0.03 (S-4) < 0.94 ± 0.02 (S-3) < 0.96 ± 0.01 (S-7) < 0.97 ± 0.01 (S-1) meq/L and 0.58 ± 0.08 (S-5) < 0.78 ± 0.06 (S-2) < 0.84 ± 0.10 (S-6) < 1.05 ± 0.10 (S-3) < 1.1 ± 0.07 (S-4) < 1.31 ± 0.09 (S-1) < 1.6 ± 0.15 (S-7) meq/L, respectively (Table 6; Fig. 2C and F). So, CAI1 and CAI2 are positive, indicating a direct exchange of Na^+ and K^+ from water with Ca^{2+} and Mg^{2+} from rock. This incident may be due to the high interaction of water with an existing rock during water flow. The condition causes the organization of a double-layered cast on the silicate clay. Since, higher positive cations dominate the interlayer, and the outside layer forms a negatively charged. Ultimately, this incident increased through the direct ion exchange process (Abderamane et al. 2013).

Irrigation water chemical facies and water types

The Piper, USSL salinity, and Durov's diagrams were plotted to evaluate chemical facies and irrigation water types. Piper and Durov's diagram is plotted based on cations (Ca^{2+}, Mg^{2+}), alkali (Na^+ and K^+), weak acid (HCO_3^-), and strong acids (SO_4^{2-}, Cl^-) (Piper 1944; Sappa et al. 2014). Further, the Piper plot depends upon the concentration of the cations and anions in milliequivalent percentage (meq %) in a central diamond field with two base triangles. The type of water depends upon the distribution of all the cations and anions in the plot. In this study, the Piper plot indicated that irrigation water was mainly rich in (1) Ca^{2+}–Cl^-–SO_4^{2-}; (2) Na^+–K^+–$CaCO_3 + HCO_3^-$ (3) Na^+–K^+–Cl^- at most of the locations (Fig. 4). In the present study areas, irrigation water is primarily derived from snow and glacial melt, dominated by Ca–SO_4 (Singh et al. 2012; Gosselin et al. 2001). This

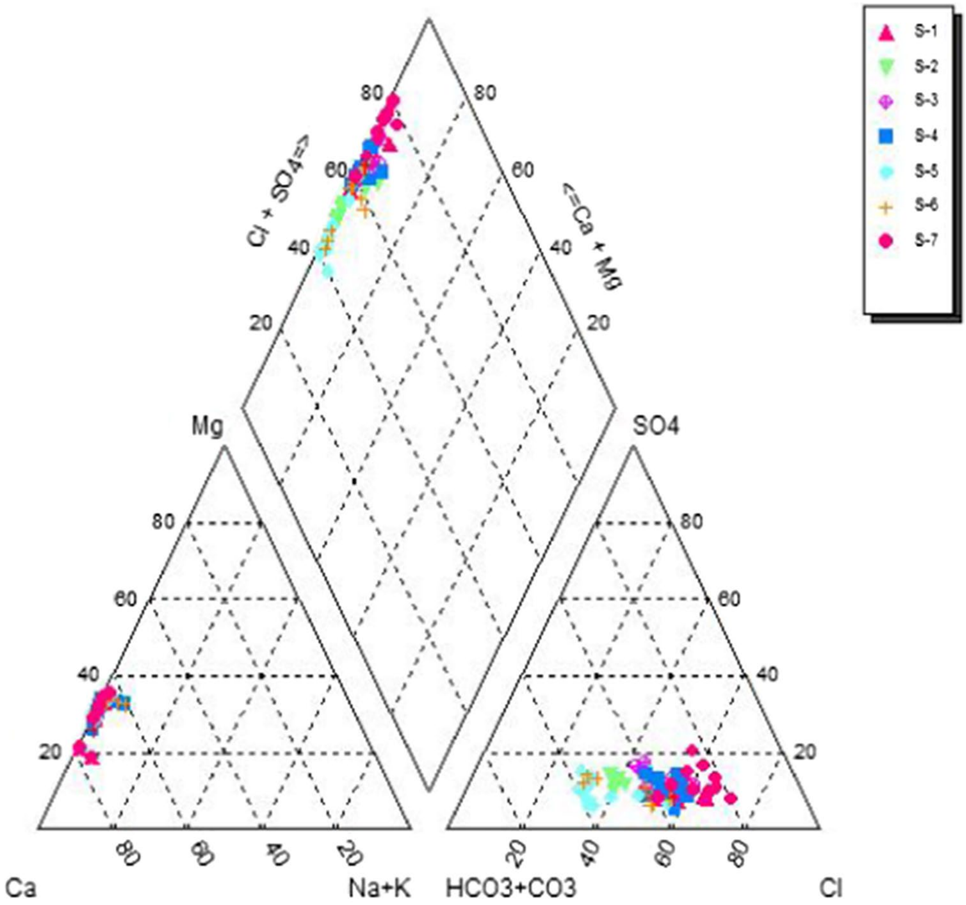


Fig. 4 Piper diagram describing the level of cationic and anionic composition of irrigation water of high altitude (Leh, Ladakh, India)

irrigation water flows on various fields and so may mix with different ions at different places. Therefore, there are chances for water evolution, mostly depending upon the host lithology. In our study, water is mainly dominated by Ca^{2+}–SO_4^{2-}; Na^+–$CaCO_3 + HCO_3^-$, and K^+–$CaCO_3 + HCO_3^-$ ions which indicate the dissolution of gypsum and carbonate rocks in the study area. Meanwhile, water also characterized by Ca^{2+}–Cl^-, Na^+–Cl^-, and K^+–Cl^- type water might be due to the silicate rock weathering process and some extent of anthropogenic activity (Jeelani et al., 2011; Bhat et al. 2014). Therefore, it has been found that, in the study area, the irrigation water evolves with different types of water due to its getting mixed up with other chemical constituents in their flowing path.

Therefore, in a broader perspective, to find the main reason behind the source of solutes, the data has been plotted in the Gibbs diagram (Gibbs 1970) (Fig. 5). The Gibbs diagram shows the dominance of rock–water interaction. Therefore, the irrigation water gets most of the solutes due to the chemical weathering process.

Further, the Durov's diagram helps identify the hydrochemical processes in water, classifying different types of water mixing, the presence of ions, and reverse ion exchange processes (Durov 1948; Li et al. 2016). This diagram is

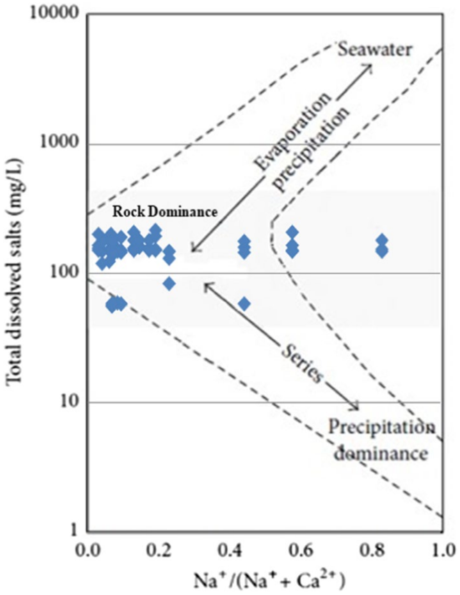


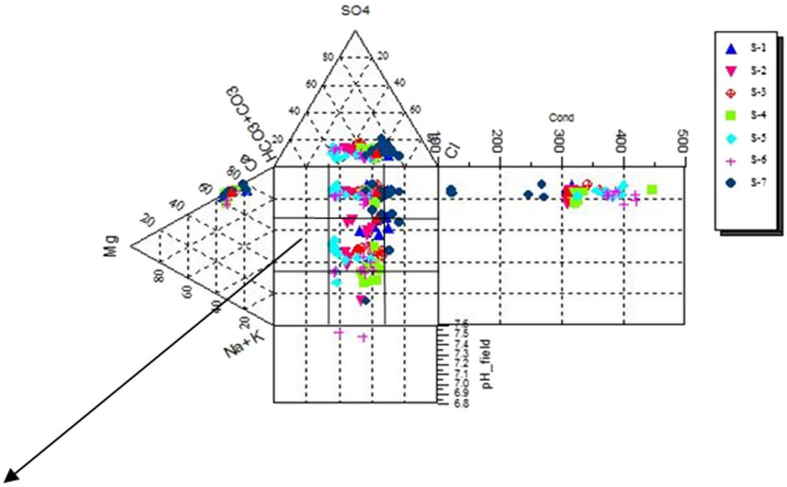
Fig. 5 Gibbs diagram representing the geochemical processes controlling irrigation water chemistry of high altitude (Leh, Ladakh, India)

delineated by two trilinear plots projected onto the middle square plot. The major ion distribution in this plot will determine the different types of water mixing (Ghesquière et al. 2015). In the present diagram, Ca^{2+} is the major cation, and among the anions, SO_4^-, CO_3^-, and HCO_3^- are prevalent. Ca^{2+}–CO_3^- and Ca^{2+}–HCO_3^- dominated water types are caused by carbonate mineral dissolution. The presence of Ca^{2+}–SO_4^- is mainly due to the gypsum dissolution process (Fig. 6) (Vasanthavigar et al. 2012; Li et al. 2016; Liu et al. 2019).

Water–rock interaction

The majority of water quality parameters are based on minerals in the water. However, the most probable and natural source for the high-altitude region may be rock weathering. So far, no study has been conducted to establish this hypothesis by analyzing the vast water quality data of high-altitude regions. The present findings based on rock–soil interaction indicate confirmatory data about the presence of weathering (Thorne 1954). Furthermore, results showed that more than one weathering process is prevalent at sampling sites S-1 to S-6. The HCO_3^-/SiO_2 parameter indicates that the silicate weathering is present at S-7. However, for the different parameters, viz. $SiO_2/(Na+K–Cl)$, $(Na+K–Cl)/(Na+K–Cl+Ca)$, $Ca/(Ca+SO_4)$, TDS, and Cl^-/sum anions, and different types of weathering processes like cation exchange, plagioclase weathering unlikely, calcium source other than gypsum–carbonate or silicates, silicate weathering, and rock weathering are found, respectively (Table 7). The presence of different types of weathering processes at such a high-altitude region might be due to a change in the global climate pattern in this scenario of global warming, which leads to a change in the hydro-geochemical process (Quade et al. 2001, 2003; Ghezzi et al. 2017; Singh et al. 2017; Pant et al. 2018; Sabin et al. 2020).

Apart from Table 7, indicating the presence of different rock–water interactions, some quantifiable plots may understate this aspect. Scatter plots on major ion chemistry allow the apprehension of the complex rock–water interaction in any region (Jeelani and Shah 2006). The $Ca^{2+}+Mg^{2+}$ versus $HCO_3^-+SO_4^{2-}$ scatter plot showed that most of the samples were distributed below the equline of the graph, indicating that the significant source of ions was silicate weathering in the study area (Fig. 7A) (Datta and Tyagi 1996). To further confirm the prevalence of silicate weathering, another scatter plot with end members of silicate and carbonate (HCO_3/Na versus Ca/Na Plot) is plotted (Fig. 7B). The plot showed the dominance of silicate weathering, further justifying the earlier findings on the prevalence of silicate weathering in the study area (Gaillardet et al. 1999). To understand the carbonate weathering process, (Ca + Mg) versus HCO_3 are plotted and presented in Fig. 7C. It has been found that most of the samples fall below the equiline of the graph, indicating the presence of carbonate weathering. Some samples were distributed away from the equiline, indicating the presence of other sources of HCO_3 (Jeelani et al. 2011; Bhat et al. 2014, 2019). The (Ca + Mg) versus (Na + K) plot showed the



1	4	7
2	5	8
3	6	9

After putting the number in the small boxes of middle rectangular space, then according to Yu et al. (2021), 1-Mixing and reverse cation exchange waters of Cl-Ca type; 2- Mixing and reverse cation exchange reactions; 3-Mixing with sea water or halite; 4-Calcite and gypsum dissolution; 5-Mixing reactions from various origins; 6-Mixing and cation exchange waters; 7-Infiltration waters of HCO_3-Ca type; 8-Cation exchange reactions; 9-Cation exchange waters of HCO_3-Na type

Fig. 6 Durov's diagram showing the type of irrigation water chemistry at high altitude (Leh, Ladakh, India)

Table 7 Rock–soil–water interaction and their categorization at different sampling locations of high altitude

Parameter	Attention Value	Conclusion	S-1(Ranbirpur)	S-2(Thiksay)	S-3(Chochot)	S-4(Shay)	S-5(Choglamsar)	S-6(Spituk)	S-7(Nimu)	Result
HCO_3-/SiO_2	> 10	Carbonate weathering	5.095	4.559	4.677	9.693	8.509	7.173	3.445	Ambiguous (S-1 to S-6); Silicate weathering (S-7)
	> 5 and < 10	Ambiguous								
	< 5	Silicate weathering								
SiO_2/(Na + K-Cl)	< 1	Cation exchange	−0.112	−0.168	−0.121	−0.087	−0.217	−0.281	−0.098	Cation exchange
	> 1 and < 2	Albite weathering								
	> 2	Ferromagnesian minerals								
(Na + K-Cl)/(Na + K-Cl + Ca)	> 0.2 and < 0.8	Plagioclase weathering possible	−0.56	−0.528	−4.412	−1.021	−0.185	−0.232	−0.606	Plagioclase weathering unlikely
	< 0.2 or > 0.8	Plagioclase weathering unlikely								
Mg/(Ca + Mg)	= 0.5 and HCO_3-/Si > 10	Dolomite weathering	0.294, 5.10	0.349, 4.56	0.197, 4.68	0.333, 9.69	0.320, 8.51	0.341, 7.17	0.304, 3.45	S-1, 4, 5, 6: Ambiguous; S-2, 3, 7: Ferromagnesian Minerals
	< 0.5	Limestone–dolomite weathering								
	> 0.5	Dolomite dissolution, calcite precipitation or seawater								
	< 0.5 and HCO_3-/Si < 5	Ferromagnesian minerals								
	> 0.5	Granitic weathering								
Ca/(Ca + SO_4)	= 0.5	Gypsum dissolution	0.935, 8.68	0.939, 8.52	0.872, 8.32	0.918, 8.12	0.921, 8.36	0.925, 8.13	0.941, 8.72	Calcium source other than gypsum—carbonate or silicates
	< 0.5 and pH < 5.5	Pyrite oxidation								
	< 0.5 and pH neutral	Calcium removal—ion exchange or calcite precipitation								
	> 0.5	Calcium source other than gypsum—carbonate or silicates								

Table 7 (continued)

Parameter	Attention Value	Conclusion	S-1(Ranbirpur)	S-2(Thiksay)	S-3(Chochot)	S-4(Shay)	S-5(Choglamsar)	S-6(Spituk)	S-7(Nimu)	Result
TDS	> 500	Carbonate weathering or brine or seawater	144	149	146	149	178	180	59	Silicate weathering
	< 500	Silicate weathering								
Cl^-/Sum Anions	> 0.8 and TDS > 500	Seawater or brine or evaporites	0.523	0.468	0.606	0.45	0.261	0.266	0.598	Rock weathering
	> 0.8 and TDS < 100	Rainwater								
	< 0.8	Rock weathering								

carbonate lithology as most of the samples remain below the equiline of the graph. Some samples located above the equiline of the graph (Fig. 7D) indicate the presence of silicate lithology as Na + K is getting higher than Ca + Mg (Jeelani et al. 2011; Bhat et al. 2014, 2019). Therefore, carbonate and silicate weathering may exist in such a broad study area. Because of the higher molar ratio of Ca/(Ca + Mg), the Ca/(Ca + Mg) versus SO_4/(SO_4 + HCO_3) plot (Fig. 7E) revealed the presence of dolomite and calcite dissolution processes. The increase of Mg with the rise of SO_4 might be due to dedolomitization or the anhydrite dissolution process (Jeelani et al. 2011; Bhat et al. 2014, 2019).

Interrelationship among sampling locations

For the suitability of irrigation water, Q-mode cluster analysis indicated the interrelationship among all the sampling locations (Fig. 8). The first cluster includes S-1, S-7, and S-4. The second cluster includes S-5 and S-6, whereas the third cluster includes S-2 and S-3. The basic principle behind this interrelationship and the dissimilarities among all these villages are variations in cations, anions, and other minerals. These parameters may vary at different sampling sites due to different rock weathering processes, higher or lower anion exchange processes, reverse exchange processes, and anthropogenic activity. If we consider the distance of all the sampling sites (S1 to S7) from the main Leh city, then Ranbirpur (S1; 38 km away from the main city), Nimu (S7; 45 km away from the main city), and Shey (S4; 30 km away from the main city) are the farthest away from the main city. This might be the possible reason behind the same type of irrigation water quality in these villages. However, Choglamsar (S5; 15 km away from the main city) and Spituk (S6; 10 km away from the main city) are very near to the main city. In these villages, the population size is comparatively larger, and they also have small industries, so anthropogenic activity is higher than in the other villages. Therefore, the same type of irrigation water evolved in these villages. Meanwhile, Thiksay (S2; 31 km away from the main city), and Chochot (S3; 25 km away from the main city) are located at a moderate distance from the main city. In these villages, pollution inputs due to anthropogenic activity are less than the S5 and S6. Hence, the moderate distance and less anthropogenic activity might impact whether it evolves into the same type of irrigation water.

Conclusion

The present study was conducted to determine irrigation water's anionic and cationic chemistry for their suitability in agricultural practices and rock–soil–water relationships in high-altitude regions of Leh, UT Ladakh, India.

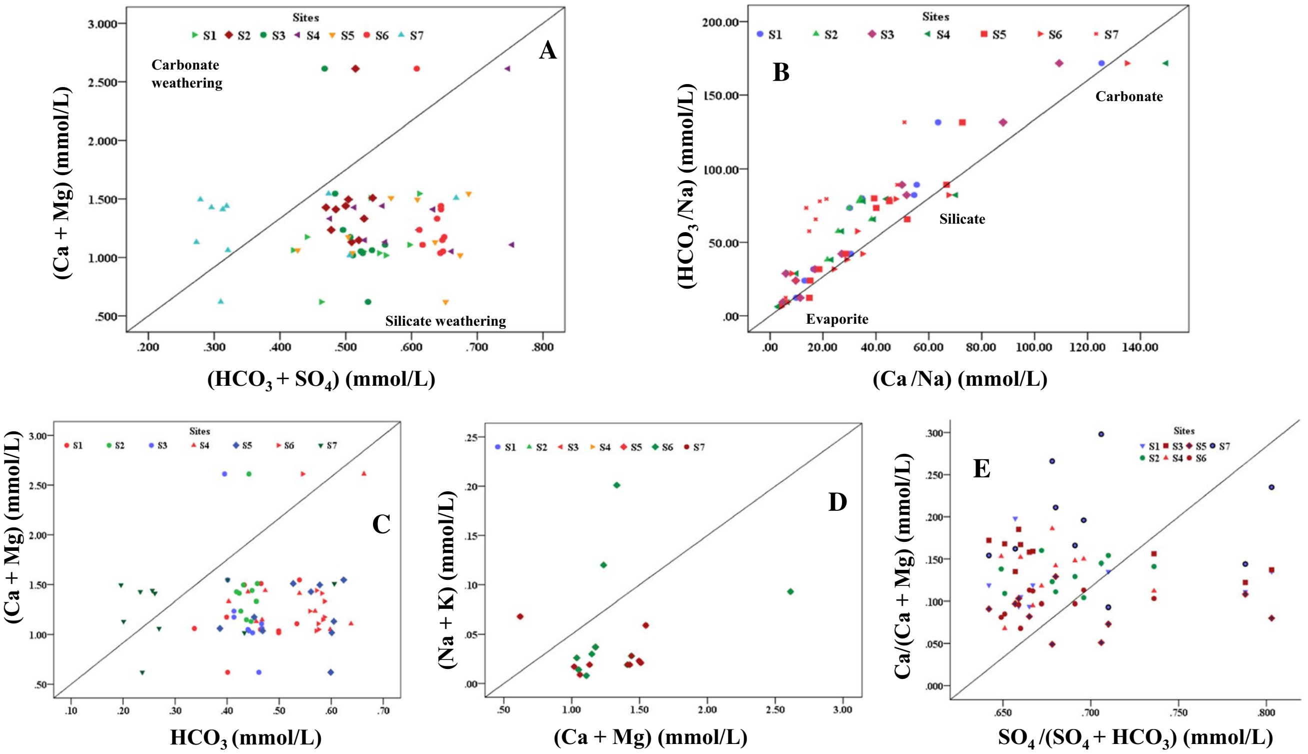


Fig. 7 **A**–**E** Scatter plots to identify the most responsible geochemical process for evolution of different water types at high altitude (Leh, Ladakh, India) (Jeelani et al., 2011; Bhat et al., 2019, 2014)

Most of the major parameter levels suggest that overall water chemistry is suitable for irrigation. Further, water is mainly dominated by Ca^{2+}, Mg^{2+} cations, and anions like HCO_3^-, SO_4^-, and CO_3^-. The Piper plot indicates that the water is mainly Ca^{2+}–Cl^-–SO_4^-, Na^+–K^+–$CaCO_3 + HCO_3$, and Na^+–K^+–Cl^- type of anions and cations. Further, rock–soil–water interaction revealed the presence of silicate and carbonate weathering along with the dissolution of gypsum in the water. The complex hydro-geochemical interaction, direct ion exchange process (CAI 1 and 2 are positive), and other anthropogenic inputs are responsible for major ion chemistry. This study also concludes that inhabitants should avoid applying metal pipes in irrigation appliances. Therefore, consistent monitoring of the irrigation water quality and a long-term water management plan is recommended for the agriculture irrigation water system and related activities.

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Author contributions AG: performed the minerals and physicochemical analysis experiments, statistical analysis, and software-based analysis using AquaChem, and drafted the main manuscript. SK, KK, and MK: helped with sampling and physicochemical analysis. VKB: conceived, designed, and coordinated this study and interpreted the data. All the authors have read and approved the final version of the manuscript.

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Data availability Data will be available from the corresponding author upon good scientific reason and request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical Approval Specific permits are not required for the described field studies, and our field studies did not involve endangered or protected species.

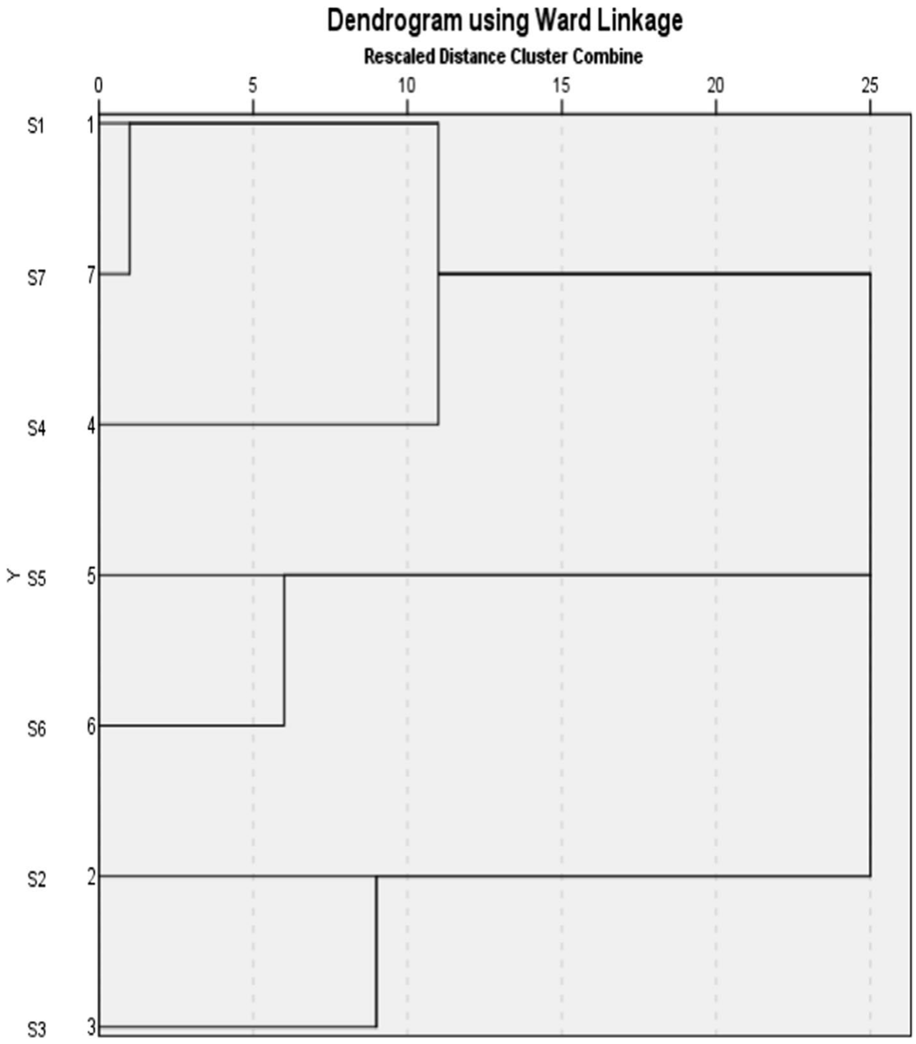

Fig. 8 Cluster analysis presenting the similarities among the sampling locations at high altitude (Leh, Ladakh, India)

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