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ORIGINAL ARTICLE

State of groundwater resource: relationship between its depth and sewage contamination in Leh town of Union Territory of Ladakh

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Abstract

Groundwater as a resource of wide-spectrum use, especially in the tourism sector, has evolved as the prime most source of water in Leh town in recent years. Unfortunately, the regulation on groundwater use and monitoring as well as scientific management of this resource is almost zero so the resource is over-exploited as well as ill managed. The skewed balance of technology required versus that already available in order to manage this fast urbanizing town is massive, and the place is already showing initial signs of management issues of waste, traffic, air and water pollution. The town is in dire need of innovative and cost-effective solutions for keeping alive its environmental sustainability quotient as it is undergoing a paradigm shift from an agricultural society into a class III urban agglomeration as per Indian Census. In the absence of constant monitoring of this resource, there is a wide data gap related with groundwater resources in Leh town, and so it is very difficult to derive an exact estimation of the water table all over the town. This paper thus gives an elaborate description of the status of groundwater resources in Leh town in dearth of baseline data. Further the risks posed by various factors which are threatening the proper management of this resource are mentioned, and the way forward for sustainable management of Leh town keeping groundwater as a focal point is rightly covered.

Keywords Leh town · Urbanization · Water quality · Deterioration

Introduction

Leh district has come a long way from 527 tourists (1974) to 146,501 tourists (2015) (Statistical Handbook 2015–16) and is ever increasing. Leh town is focal point of this region and bears initial boon or bane of the tourism industry. The success of Bollywood film '3 idiots' has immensely contributed in increasing the national tourist influx in addition to international number with more or less stable throughout this period from 2001 to 2011 (Dolma 2015). Simultaneously, the administration carries out various destination promotion events and other marketing attributes like Ladakh Festival for culture and tourism promotion. Also, it cooperates robustly with institutions which organize events like Ladakh International Film Festival (LIFF) which is a cost-effective means of destination marketing without shelling huge sums of monetary resources, thereby saving significant amount of exchequer money. LIFF which was organized in 2012 helped immensely in attracting tourists towards this place. It was a joint effort by the state government of Jammu and Kashmir along with the district administration of Leh. Even the slogan of the festival 'Come explore the magic of Cinema in the magical land of Ladakh' was adopted keeping in mind to promote the destination of Leh as much as possible as an offbeat and out-of-this-world place (Kishore 2013).

In order to support this sector, various resources like land, water and infrastructures are required for smooth and efficient functioning. As tourism is a water-intensive industry, it is highly dependent on groundwater resources of the area. Currently PHE (Public Health Engineering) department of Leh district is supplying 40 lpcd (litres per capita daily) of water to the residents of Leh town, mostly in few summer months through lined water supplies/pipes network. For the rest of the year due to freezing temperatures, bursting of

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pipes occurs and water is supplied through tanker services much lesser than 40 lpcd. Water demand increases manifold during summer months due to influx of tourists, and groundwater resources are the only avenue to meet this demand.

Tourism undoubtedly puts acute stress on the quality and quantity of available resources in any booming tourist destination, but adverse stresses are more pronounced in the developing world, where necessary management practices are not followed due to dearth of funds or non-availability of cost-effective technologies. Furthermore with quantity-focused stress, there is an even greater risk of quality deterioration through contamination of groundwater, especially in areas where waste water treatment is inadequate or not at all available. The town of Leh is adopting water-intensive flush toilets and constructing soak pits for waste water disposal in the absence of any sewerage system which is a major shift from an age-old traditional dry sanitation practice. In such a case, the threat of shallow groundwater pollution is enormous in the town as the sewerage system being laid currently is only partial and will take years to fully function.

Study area

The land of Ladakh is so barren and passes so high that it was almost cut off from the rest of the Indian mainland. Since ancient times, Ladakh was an agricultural society, but northern Leh town of India located near key mountain passes was a trading network hub, even during those times. Leh town was a part of the great trading Silk Route which connected Central Asia, South Asia and Tibet, but this route was opened only during summers and cut off during winters due to heavy snow. So, this town was an important resting location for trading troupes, especially during summers, but this scenario was true to core before independence of India. After closing off of the two borders with China and Pakistan, Leh town was transformed into a remote cut-off place in popular Indian psyche. With the closing of centuries' famous trade route known popularly as the Silk Route, Leh town took a U-turn from a cosmopolitan outlook towards one of the remotest places in India (Fewkes 2012).

Ladakh region is a high-altitude 'Cold Desert' in the north of India in Jammu and Kashmir state which consists of Leh and Kargil districts before passing of J&K Reorganization Act on 31st October 2019 in the Indian Parliament. After passing of act, the cold desert of Ladakh became Union Territory of Ladakh and as of present is being administered directly by the Central Government of India. Cold deserts are usually confined to high altitude and circumpolar regions. Ladakh is the largest cold desert zone in Trans-Himalayas (Ballabh et al. 2007). It is blessed with the most beautiful and highest lakes like Pangong and Tsomoriri and enchanting valleys like Indus and Suru. Its glaciers, glaciated topography, steep gorges, cataracts, alluvial fans, river terraces and socio-cultural milieu present large potential for explorers, trekkers, leisure-seekers and academicians (Jina 1994). This land is also popularly known as land of high rising passes or 'Little Tibet' (Gairola et al. 2014). The famed Nubra valley lies in Ladakh, and this name in local dialect 'Dumra' literally translates into garden or green valley (Joshi et al. 2005). Nubra also has vast vegetation characteristics like scattered low bushes, sparsely covered tussock grasslands, herbaceous formation, sedge meadows and stony deserts (Joshi et al. 2006). Ladakh and Karakoram ranges have been an area of attraction for earth scientists as well, to study the dynamic relationship between Indian and Eurasian plates (Pant et al. 2005).

Only in 1974 when the region was partially opened for tourism, this area was truly opened for explorers from rest of the world. Leh town being the main administrative centre and having air connectivity year round has a booming tourism industry in the present times. Earlier, agriculture was the main source of livelihood in this region which in current times is getting a respite from other economic avenues like tourism industry and jobs created by this sector. Another imminent sector of economic opportunities is created recently due to large permanent deployment of Indian army personnel. Enhanced acceptance of strategic location and importance of this region in maintaining regional hegemony is fully supported by Government of India. This area has the famed Siachen glacier which is a vantage point for India and its security.

Leh town

The patterns of settlements in Leh district are mainly located in between the river valleys situated below the mighty Himalayan mountains, and these valleys are formed especially due to erosional activities of glaciers, located in between these mountain ranges from millennia. Leh valley is a U-shaped valley formed due to such erosional activities and morainic deposits that underlie the plain consisting of boulders, cobbles, pebbles embedded in an arenaceous matrix and lake deposits comprising predominantly of clays, sandy clays and silt, indicating remains of lake deposits (CGWB 2009). Leh town lies in Leh valley lying between 34° 8′ N to 34°13′ N latitude and 77° 32′ E to 77° 38′ E longitude totalling an area of 9.15 km^2 (Fig. 1).

Methodology

In order to successfully carry out the proposed study, a scientific and thoroughly tested methodology which is technically sound was adopted. A total of 30 water

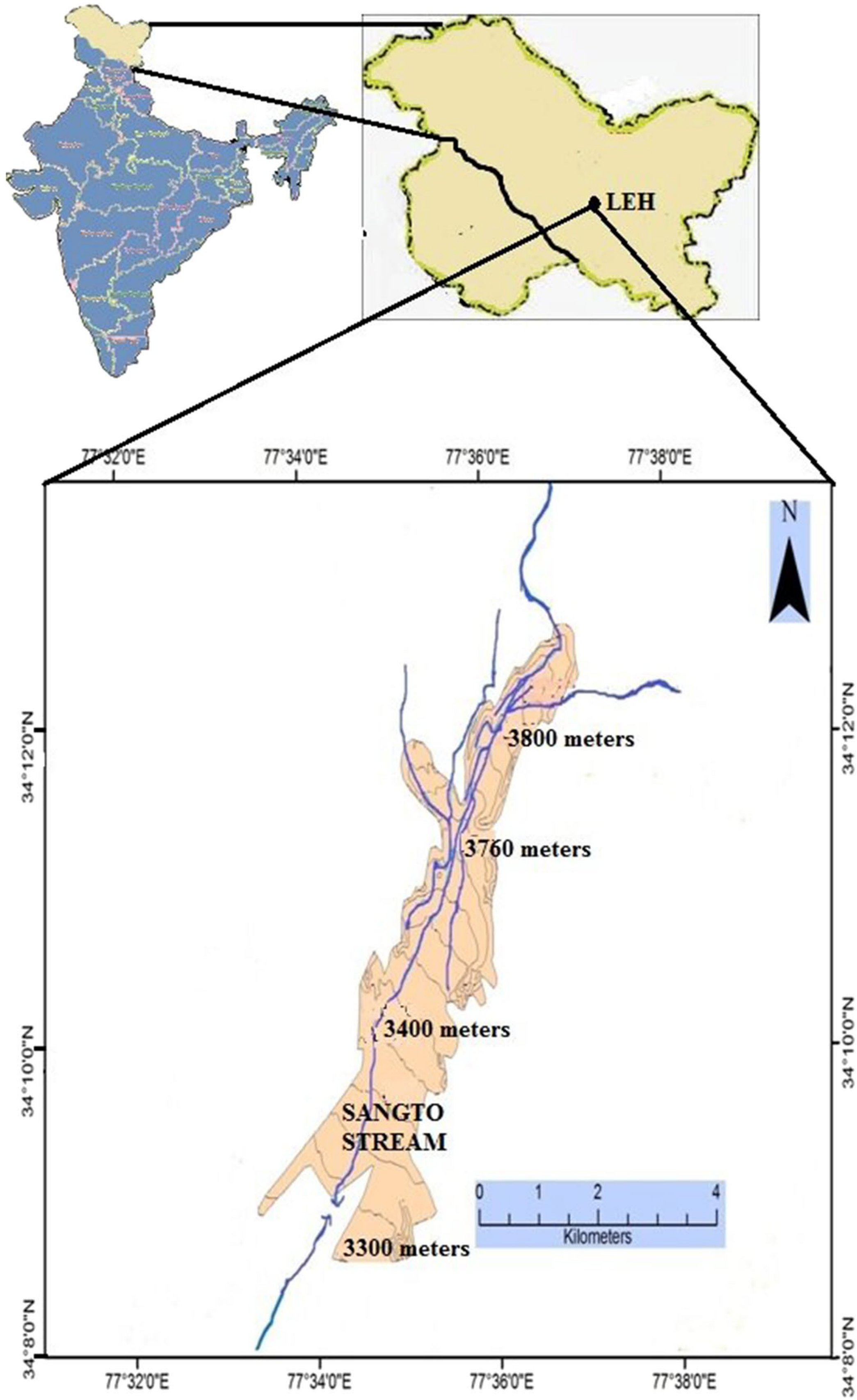

Fig. 1 Location of Leh town, the study area

samples especially from groundwater were collected from bore wells, springs and from hand pumps in the pre-monsoon season month of May (2013 and 2014) and post-monsoon season month of October (2013 and 2014) which coincided with the pre- and post-monsoon season months simultaneously, so as to evaluate its fitness for drinking purposes and other domestic uses. The groundwater samples were analysed in physicochemical laboratory of Geology Department, Panjab University. The water samples were characterized for various parameters in accordance with the standard methodology given by APHA (2005) for both the seasons (Tables 1, 2). Parameters like Na^+, K^+, Cl^-, SO_4^{2-} were converted into meq/l by multiplying with their respective standard multiplying factors. Further, *r*1 (*Base-Exchange*) and *r*2 (*Meteoric Genesis Indices*) were evaluated from the above data in meq/l. Totally, 30 samples of groundwater were taken from all over Leh town and its fringe areas located in Leh district of the Union Territory of Ladakh (Fig. 2).

Data deficient on groundwater lithology and classification based on base-exchange and meteoric genesis index

(*r*1) *Base-exchange:* Groundwater properties, on the basis of predominantly consisting chemicals, particularly Na^+–SO_4^{2-} and Na^+–HCO_3^- types, were classified according to the above two types. The equation to calculate (*r*1) base-exchange is as follows:

Table 1 Results of groundwater sample analysis during pre-monsoon/pre-tourist season

S. no.	Location	pH	EC (µS/cm)	TDS	TH	Ca^{2+}	Mg^{2+}	Na^+ (mg/l)	K^+	CO_3^{2-}	HCO_3^-	Cl^-	F^-	NO_3^-	SO_4^{2-}	WQI
1	Gyalung	7.6	223	146	100	53.64	9.88	7.1	3.3	BDL	52	8	BDL	0.44	7.94	34.81
2	Gangles	7	210	140	80	52.6	22.45	8.7	3.2	BDL	33	5.1	BDL	1.8	36.45	19.87
3	Gompa	7	283	186	110	54.48	11.83	9	3	BDL	16	5.1	BDL	0.01	6.01	12.68
4	Sankar	7	205	134	90	45.23	12.32	8	5.1	BDL	59	10	BDL	5	5.4	12.35
5	Yourtung	7	234	160	200	72.8	20.04	7	4.7	BDL	27	12	BDL	0.01	8.67	19.43
6	Khagshal	7.5	256	168	190	80	16.68	17	4.9	BDL	152	16	BDL	0.01	28.45	39.06
7	Changspa	7.2	287	187	132	52.8	18.17	7.1	3.2	BDL	28	10	BDL	0	5.4	23.87
8	Chubi	7.5	248	308	100	52.8	10.37	15.1	5.9	BDL	139	14	BDL	0	6.08	31.73
9	LEDeG	7.1	275	159	120	53.64	14.76	6.5	3.2	BDL	62	5	BDL	0.2	6.1	18.25
10	Karzoo	7	303	199	114	56.16	11.83	7.2	3.5	BDL	40	7	BDL	0	5.4	12.95
11	U.Tuckha	7.2	439	166	92	53.64	7.93	6.6	3.6	BDL	132	5.1	BDL	0	5.4	18.50
12	Middle Sch	8	387	260	200	84	19.02	6.2	4.3	BDL	38	12.1	BDL	0.01	19.08	59.23
13	Fort Road	7.5	549	361	188	57.85	28.91	10.3	3.4	BDL	52	6.4	BDL	1	9.01	42.76
14	Shenam	7	324	250	140	58.69	16.71	9.2	4.3	BDL	56	5.6	BDL	0	5.4	16.13
15	16BRTF	7.1	295	194	110	59.53	8.9	17	3.3	BDL	112	18	BDL	0.22	5.4	15.85
16	Zorawar Ft	7.5	424	270	150	56.42	14.56	10.5	3.7	BDL	84	13	BDL	5.07	48.17	36.92
17	Skara Spring	7.6	575	202	134	41.87	25	15.3	3.9	BDL	41	2.97	BDL	0.12	9.5	42.39
18	Skalzangling	8	403	269	100	58.64	8.8	10.9	7.6	BDL	62	9.67	BDL	10.05	11.06	51.09
19	Housing Cl	7	849	393	170	55.32	25.98	20.8	4.8	BDL	40	26	BDL	0	9.7	21.79
20	DIHAR	7.5	660	434	142	40.19	27.93	16.1	3.6	BDL	92	14	BDL	0	6.63	40.62
21	Murtse	7.1	357	236	170	56.46	14.06	8.47	3.7	BDL	48	7.71	BDL	0.01	8.01	18.62
22	Ibex Colony	7	423	279	156	63.73	17.68	7.6	3.8	BDL	36	6.9	BDL	0.5	6.76	17.30
23	ITBP Leh	7.7	351	230	170	80.37	16.09	10.8	4.8	BDL	112	12.3	BDL	3.07	21.47	46.11
24	MES IIIrd	7.5	347	231	144	65.42	13.78	7.1	3.3	BDL	98	10	BDL	0	5.39	34.58
25	MES Spituk	7.5	482	317	178	55.32	27.93	12.1	4.3	BDL	108	9	BDL	0	5.85	41.86
26	Airforce Stn	7.6	200	137	150	62.87	12.03	7.6	4.4	BDL	88	9.34	BDL	3.07	28.45	38.45
27	CIBS	7.5	301	198	167	67.21	29.07	8.7	4.6	BDL	98	9.23	BDL	2.8	21.45	44.16
28	Zivey Tsal	7.7	835	431	130	31.77	29.88	36.9	5.2	BDL	136	4.2	BDL	0	26.23	49.80
29	Choglamsar	8	496	326	164	48.6	28.42	22.6	3.4	BDL	142	5.1	BDL	0	18.01	61.52
30	SOS Village	7.6	367	240	250	76.21	26.08	26.6	6.6	BDL	162	16.3	BDL	0.01	28.51	48.25

BDL below detectable limit

Table 2 Results of groundwater sample analysis during post-monsoon/post-tourist season

S. no.	Location	pH	EC (μS/cm)	TDS	TH	Ca^{2+}	Mg^{2+}	Na^{+} (mg/l)	K^{+}	CO_3^{2-}	HCO_3^{-}	Cl^{-}	F^{-}	NO_3^{-}	SO_4^{2-}	WQI
1	Gyalung	7.6	220	131	94	51.11	9.88	7.5	3	BDL	51	9	BDL	0.42	6.01	32.59
2	Gangles	7.4	190	130	90	52	23	8	3.5	BDL	30	2.5	BDL	1.5	36.03	32.63
3	Gompa	7.1	260	172	100	51.2	12.83	9.2	3.1	BDL	16	3.1	BDL	0	6.5	15.66
4	Sankar	7.5	201	130	80	41.87	13.6	7.9	5.2	BDL	52	9.1	BDL	7.1	4.8	31.54
5	Yourtung	7	220	150	194	70.01	19.2	7.3	4.2	BDL	28	11.5	BDL	0.02	7.1	17.41
6	Khagshal	7.5	270	180	180	74.6	16.01	17	5.2	BDL	143	12	BDL	0.01	27.23	34.97
7	Changspa	8	280	178	122	45.23	20.12	6.3	3.1	BDL	24	10	BDL	0	4.01	52.24
8	Chubi	7.6	220	151	98	41.02	11.71	15.5	5.7	BDL	135	15	BDL	0	5.3	33.42
9	LEDeG	7.2	262	171	112	43.55	15.66	6.7	3	BDL	61	4.5	BDL	2.77	5.7	20.96
10	Karzoo	8	300	186	120	51.96	10.85	7	3.3	BDL	40	6.4	BDL	0.3	4.6	48.05
11	U.Tuckha	8	400	269	72	50.27	8.416	6.1	3.1	BDL	127	4.4	BDL	0.5	3.7	46.75
12	Middle Sch	8	340	231	198	87	19.56	6.6	4.5	BDL	37	11.8	BDL	0	18.01	56.14
13	Fort Road	7.4	529	320	172	53.64	34.01	9.8	3.7	BDL	46	5.2	BDL	1	8.47	38.97
14	Shenam	7	365	237	130	52.8	22.68	8.9	3.9	BDL	53	5	BDL	0	4.8	17.61
15	16BRTF	7.6	286	186	100	53.64	9.88	16	3.1	BDL	111	17.2	BDL	0.5	4.2	33.12
16	Zorawar Ft	7.2	387	255	137	53	15	9.5	3.9	BDL	80	12.3	BDL	4.8	46.67	22.77
17	Skara Spring	7.5	556	369	112	38.5	26.6	14.4	3.6	BDL	40	1.34	BDL	0.1	7.8	37.13
18	Skalzangling	7.1	390	259	102	60	8.1	11.2	7.3	BDL	62	8.01	BDL	9.5	10.8	16.50
19	Housing Cl	7.2	826	560	150	52	23.05	18.8	4.1	BDL	35	25.4	BDL	0.01	8.1	26.06
20	DIHAR	7.6	568	412	138	35.13	29.88	15.1	3.1	BDL	93	13.7	BDL	0.01	5.01	42.52
21	Murtse	7.1	360	243	176	58	15	8.5	3.9	BDL	48	6.4	BDL	0	7.96	18.01
22	Ibex Colony	7.4	411	256	138	60.37	15.24	7.2	3.2	BDL	51	9	BDL	0.42	6.01	29.89
23	ITBP Leh	7.3	302	200	172	77	17.01	10.03	4.9	BDL	35	6.3	BDL	3.18	5.43	28.89
24	MES IIIrd	7.7	321	212	134	59.52	14.76	6.8	3	BDL	113	11.5	BDL	3.05	19.98	39.87
25	MES Spituk	7.4	461	306	152	50.27	25.52	11.2	4.1	BDL	93	9.4	BDL	0.01	4.7	33.98
26	Airforce Stn	7.2	210	145	154	65.07	12.16	8.2	4	BDL	110	7.8	BDL	0.01	4.3	21.45
27	CIBS	8.1	501	180	158	58.76	28.02	10.1	3.2	BDL	85	8.24	BDL	3	25.56	62.21
28	Zivey Tsal	7.6	820	510	120	30.09	28.42	32.8	4.7	BDL	100	8.65	BDL	2.1	20.8	41.74
29	Choglamsar	8	488	316	142	42.7	26.47	20.6	3	BDL	133	4.3	BDL	0.04	25.78	56.08
30	SOS Village	7.4	356	235	220	72.1	27.3	25.9	6.1	BDL	143	4.8	BDL	0.01	16.89	37.38

BDL below detectable limit

$$r1 = \left(\mathrm{Na}^{+} - \mathrm{Cl}^{-}\right)/\mathrm{SO}_4^{2-}.$$

Now, the index of base-exchange is denoted by $r1$, and in meql/l the various concentrations of Na^+, Cl^- and SO_4^{2-} ions are depicted. The sources of groundwater are of Na^+-SO_4^{2-} type when $r1 < 1$, and also the sources of groundwater are Na^+-HCO_3^- type when $r1 > 1$. As per ($r1$), base-exchange index types about 56.66% and 43.33% samples of water of groundwater were categorized as Na^+-SO_4^{2-} type, whereas 43.33% and 56.66% were classified in Na^+–HCO_3^- during pre- and post-tourist seasons, respectively, which is also coinciding with pre- and post-monsoon seasons simultaneously. This could be attributed to the geological formations through which groundwater has traversed (Table 3).

($r2$) *Meteoric genesis indices*: (Soltan 1998) As per meteoric genesis indices, groundwater can be categorized into two types after calculating from the below equation:

$$r2 = \left[\left(\mathrm{Na}^{+} + \mathrm{K}^{+}\right) - \mathrm{Cl}^{-}/\mathrm{SO}_4^{2-}\right]$$

The index of meteoric genesis is indicated by $r2$, and in meq/l the concentrations of Na^+, K^+, Cl^- and SO_4^{2-} are evaluated. In case of deep meteoric water percolation type, $r2 < 1$, and in case of shallow meteoric water percolation type, $r2 > 2$.

As per this index, the sources of water of groundwater that is 56.66% and 70% during pre- and post-monsoon, respectively, were categorized as shallow meteoric water percolating type. Also, 43.33% and 30% of the remaining samples of groundwater out of the total 30 samples

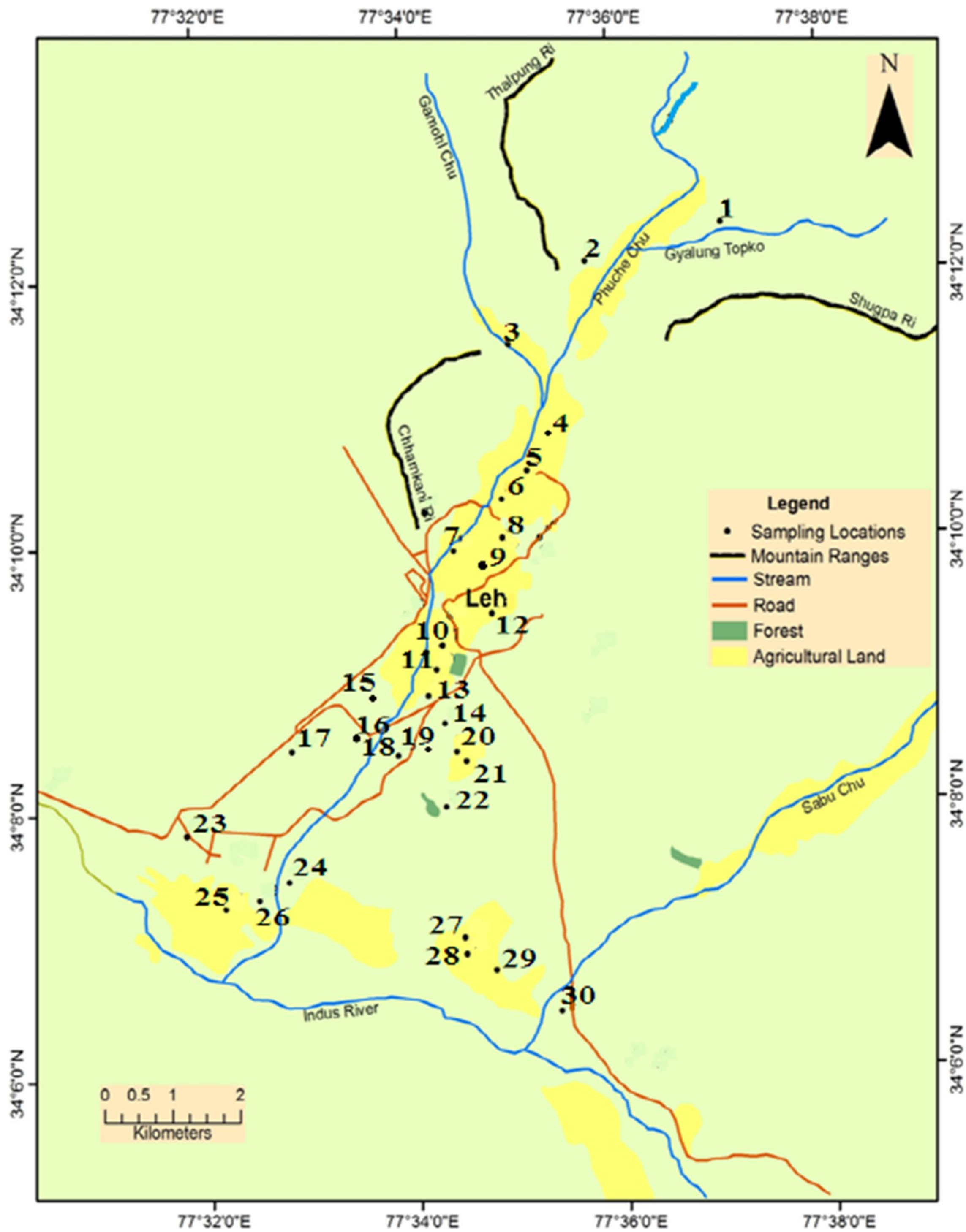

Fig. 2 Location map of groundwater sampling sites

were categorized as deep meteoric percolating water type simultaneously during pre- and post-monsoon seasons, respectively (Table 3).

Threat of contamination from raw sewage pollution in the shallow groundwater source points in Leh town

Frequent present/absent testing for faecal contamination is conducted in the main district hospital from various

Table 3 Classification of groundwater according to different criteria

Sample no.	Pre-monsoon								Post-monsoon							
	Cl^-		HCO_3^-		SO_4^{2-}		Base-exchange ($r1$)	Meteoric genesis ($r2$)	Cl^-		HCO_3^-		SO_4^{2-}		Base-exchange ($r1$)	Meteoric genesis ($r2$)
	meq/l	Class	meq/l	Class	meq/l	Class			meq/l	Class	meq/l	Class	meq/l	Class		
1	0.23	Normal	0.84	Below Normal	0.17	Normal	Na^+-SO_4^{2-}	Deep	0.25	Normal	0.84	Below Normal	0.13	Normal	Na^+-SO_4^{2-}	Shallow
2	0.14	Normal	0.49	Below Normal	0.76	Normal	Na^+-SO_4^{2-}	Deep	0.07	Normal	0.49	Below Normal	0.75	Normal	Na^+-SO_4^{2-}	Deep
3	0.14	Normal	0.26	Below Normal	0.13	Normal	Na^+–HCO_3^-	Shallow	0.09	Normal	0.26	Below Normal	0.14	Normal	Na^+–HCO_3^-	Shallow
4	0.28	Normal	0.85	Below Normal	0.11	Normal	Na^+-SO_4^{2-}	Deep	0.26	Normal	0.85	Below Normal	0.10	Normal	Na^+-SO_4^{2-}	Shallow
5	0.34	Normal	0.46	Below Normal	0.18	Normal	Na^+-SO_4^{2-}	Deep	0.32	Normal	0.46	Below Normal	0.15	Normal	Na^+-SO_4^{2-}	Deep
6	0.45	Normal	2.34	Normal	0.59	Normal	Na^+-SO_4^{2-}	Deep	0.34	Normal	2.34	Normal	0.57	Normal	Na^+-SO_4^{2-}	Deep
7	0.28	Normal	0.39	Below Normal	0.11	Normal	Na^+-SO_4^{2-}	Deep	0.28	Normal	0.39	Below Normal	0.08	Normal	Na^+-SO_4^{2-}	Deep
8	0.39	Normal	2.21	Normal	0.13	Normal	**Na^+–HCO_3^-**	Shallow	0.42	Normal	2.21	Normal	0.11	Normal	**Na^+–HCO_3^-**	Shallow
9	0.14	Normal	1.00	Below Normal	0.13	Normal	Na^+–HCO_3^-	Shallow	0.13	Normal	1.00	Below Normal	0.12	Normal	Na^+–HCO_3^-	Shallow
10	0.20	Normal	0.66	Below Normal	0.11	Normal	**Na^+–HCO_3^-**	Shallow	0.18	Normal	0.66	Below Normal	0.10	Normal	**Na^+–HCO_3^-**	Shallow
11	0.14	Normal	2.08	Normal	0.11	Normal	Na^+–HCO_3^-	Shallow	0.12	Normal	2.08	Normal	0.08	Normal	Na^+–HCO_3^-	Shallow
12	0.34	Normal	0.61	Below Normal	0.40	Normal	Na^+-SO_4^{2-}	Deep	0.33	Normal	0.61	Below Normal	0.37	Normal	Na^+-SO_4^{2-}	Deep
13	0.18	Normal	0.75	Below Normal	0.19	Normal	**Na^+–HCO_3^-**	Shallow	0.15	Normal	0.75	Below Normal	0.18	Normal	**Na^+–HCO_3^-**	Shallow
14	0.16	Normal	0.87	Below Normal	0.11	Normal	Na^+–HCO_3^-	Shallow	0.14	Normal	0.87	Below Normal	0.10	Normal	Na^+–HCO_3^-	Shallow
15	0.51	Normal	1.82	Below Normal	0.11	Normal	Na^+–HCO_3^-	Shallow	0.49	Normal	1.82	Below Normal	0.09	Normal	Na^+–HCO_3^-	Shallow
16	0.37	Normal	1.31	Below Normal	1.00	Normal	Na^+-SO_4^{2-}	Deep	0.35	Normal	1.31	Below Normal	0.97	Normal	Na^+-SO_4^{2-}	Deep
17	0.08	Normal	0.66	Below Normal	0.20	Normal	Na^+–HCO_3^-	Shallow	0.04	Normal	0.66	Below Normal	0.16	Normal	Na^+–HCO_3^-	Shallow
18	0.27	Normal	1.02	Below Normal	0.23	Normal	Na^+-SO_4^{2-}	Shallow	0.23	Normal	1.02	Below Normal	0.22	Normal	Na^+–HCO_3^-	Shallow
19	0.73	Normal	0.57	Below Normal	0.20	Normal	Na^+-SO_4^{2-}	Shallow	0.72	Normal	0.57	Below Normal	0.17	Normal	Na^+-SO_4^{2-}	Shallow
20	0.39	Normal	1.52	Below Normal	0.14	Normal	Na^+–HCO_3^-	Shallow	0.39	Normal	1.52	Below Normal	0.10	Normal	Na^+–HCO_3^-	Shallow
21	0.22	Normal	0.79	Below Normal	0.17	Normal	Na^+-SO_4^{2-}	Shallow	0.18	Normal	0.79	Below Normal	0.17	Normal	Na^+–HCO_3^-	Shallow
22	0.19	Normal	0.57	Below Normal	0.14	Normal	Na^+-SO_4^{2-}	Shallow	0.18	Normal	0.57	Below Normal	0.11	Normal	Na^+–HCO_3^-	Shallow
23	0.35	Normal	1.85	Below Normal	0.45	Normal	Na^+-SO_4^{2-}	Deep	0.32	Normal	1.85	Below Normal	0.42	Normal	Na^+-SO_4^{2-}	Deep
24	0.28	Normal	1.52	Below Normal	0.11	Normal	Na^+-SO_4^{2-}	Deep	0.27	Normal	1.52	Below Normal	0.10	Normal	Na^+-SO_4^{2-}	Shallow
25	0.25	Normal	1.80	Below Normal	0.12	Normal	Na^+–HCO_3^-	Shallow	0.22	Normal	1.80	Below Normal	0.09	Normal	Na^+–HCO_3^-	Shallow
26	0.26	Normal	1.39	Below Normal	0.59	Normal	Na^+-SO_4^{2-}	Deep	0.23	Normal	1.39	Below Normal	0.53	Normal	Na^+-SO_4^{2-}	Deep
27	0.26	Normal	1.64	Below Normal	0.45	Normal	Na^+-SO_4^{2-}	Deep	0.24	Normal	1.64	Below Normal	0.43	Normal	Na^+-SO_4^{2-}	Deep
28	0.12	Normal	2.18	Normal	0.55	Normal	Na^+–HCO_3^-	Shallow	0.12	Normal	2.18	Normal	0.54	Normal	Na^+–HCO_3^-	Shallow
29	0.14	Normal	2.34	Normal	0.37	Normal	Na^+–HCO_3^-	Shallow	0.14	Normal	2.34	Normal	0.35	Normal	Na^+–HCO_3^-	Shallow
30	0.46	Normal	2.75	Normal	0.59	Normal	Na^+-SO_4^{2-}	Deep	0.46	Normal	2.75	Normal	0.58	Normal	Na^+–HCO_3^-	Shallow

Bold values highlight the areas which got contaminated with sewage at one point of time urbanized parts of the region, but threat from point sources of raw sewage disposal from flush toilets is evident with the detection of coliform bacteria in post-tourist season in 2013 in a drinking water source from a hand pump in Chubi area of Leh town which was tapped from an earlier artesian spring confirmed during reconnaissance survey.

According to Table 3, sample no. 8, which is Chubi hand pump, falls in the shallow meteoric genesis of water source, thus indicating shallow origin even though in 2013 pre-tourist season and both pre- and post-tourist seasons in 2014 no bacterial presence was detected out of the 30 groundwater samples analysed through standard procedures (APHA 2005) in Leh town. Exhaustive data unavailability regarding borewell lithological units and point sewage pollution sources are major hindrances in concluding any relationship. In spite of large data being absent, this contamination incident might indicate the intermittent dependence on point sources of pollution in contamination of shallow spring sources. There are many non-reported cases where earlier natural springs in spite of non-drying but due to rare cases of sewage contamination are now shunned by locals. These incidents were found during the reconnaissance phase of this study ultimately indicating threats of raw sewage disposal and groundwater pollution issues, especially shallow sources of groundwater. Some of the groundwater sources which reported incidents of water contamination with raw sewage at any point of time in past several years surprisingly fall in shallow meteoric genesis indices which are mentioned in Table 4.

The contamination incidents and their locations all falling in shallow groundwater zones indicate threat of sewage pollution in such sources of groundwater and the looming crisis of sewage management, in the event of an STP plant still under construction phase in Leh town. The sample numbers, 10 and 13 were not detected with faecal contamination in either 2013 or 2014, but the above incidents of sewage contamination were acknowledged by the residents in 2013 during a reconnaissance survey undertaken in that year. Tourism undoubtedly puts acute stress on the quality and quantity of available resources in any booming tourist destination, but adverse stresses are more pronounced in the developing world where necessary management practices are not followed due to dearth of funds or non-availability of cost-effective technologies. Furthermore with quantity-focused stress, there is an even greater risk of quality deterioration through contamination of groundwater, especially in areas where waste water treatment is inadequate or not available. The town of Leh is adopting water-intensive flush toilets and constructing soak pits for waste water disposal in the absence of any sewerage system which is a major shift from an age-old traditional dry sanitation practice. In such a case, the threat of shallow groundwater pollution is enormous.

Table 4 Contaminated groundwater sources and their depths

Sample no	Location	Year of sewage contamination	Meteoric genesis ($r1$)
8	Chubi	2013	Shallow
10	Karzoo	1999	Shallow
13	Fort Road	2011	Shallow

Groundwater chemistry controlled by certain mechanisms

A diagram was proposed by Gibbs (1970) to derive a link between the chemical compositions of groundwater as per the aquifer lithologies in which they were confined. In order to get a deeper grasp and understanding of the various processes of chemical interaction of water within the aquifer lithologies like precipitation rock–water interaction and evaporation on the chemistry of groundwater in the concerned study area, the plot given by Gibbs was used. He further showed that if TDS (total dissolved solids) is pointed with respect to $(Na^+ + K^+)/(Na^+ + K^+ + Ca^+)$ concentration, it will show the controlling mechanism of groundwater chemistry. The chemistry of groundwater is regulated by major mechanisms, three in total particularly: (a) Evaporation, (b) Precipitation and (c) Rock dominance.

The following equations given below are used to calculate Gibbs ratios:

$$\text{(Cation) Gibbs ratio I} = \left[\left(Na^+ + K^+\right)/\left(Na^+ + K^+ + Ca^+\right)\right]$$
$$\text{(Anion) Gibbs ratio II} = \left[Cl^-/\left(Cl^- + HCO_3^-\right)\right]$$

whereas in meq/l the concentration of ions is evaluated.

Gibbs ratio is calculated separately for anions and cations. Gibbs ratios of water samples are plotted against their respective total dissolved solids to assess the functional sources of dissolved chemical constituents in groundwater, as shown in Figs. 3 and 4, for pre- and post-monsoon seasons, respectively.

The anions and cations for Gibbs ratios for both pre-monsoon and post-monsoon seasons are described in the above figures. A glance and interpretation from the above figures give an indication that the groundwater samples of the study area lie in the rock dominance zone. This establishes the fact that a strong interaction is present among the lithological units of aquifer where the groundwater is present and the groundwater encompassing that lithological space.

Hence, it can be derived that carbonate weathering processes are responsible for the type of groundwater chemistry in the study region.

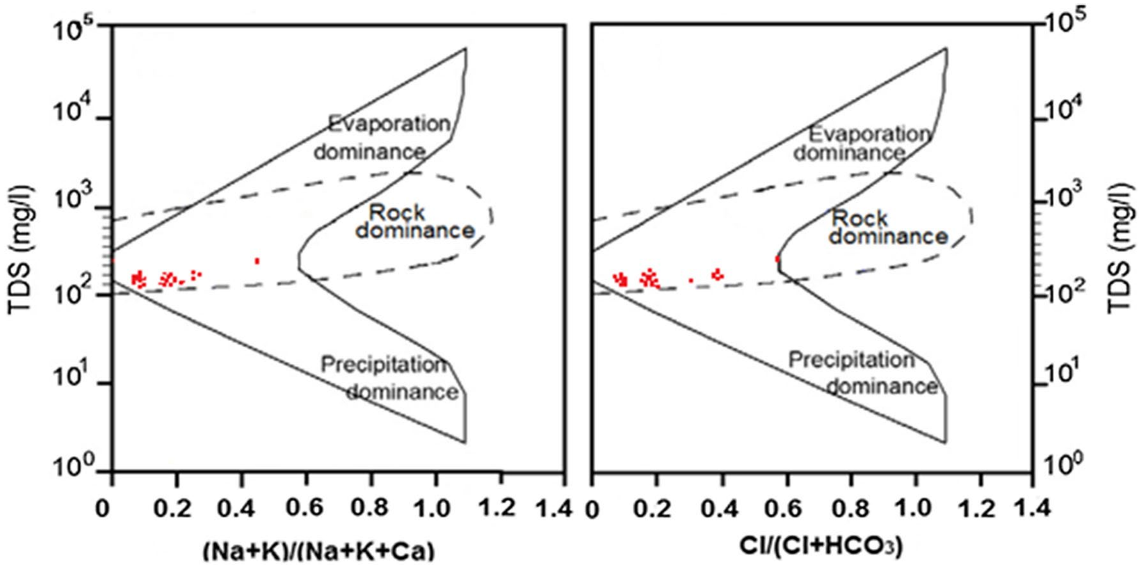

Fig. 3 Gibbs ratio for groundwater in pre-monsoon

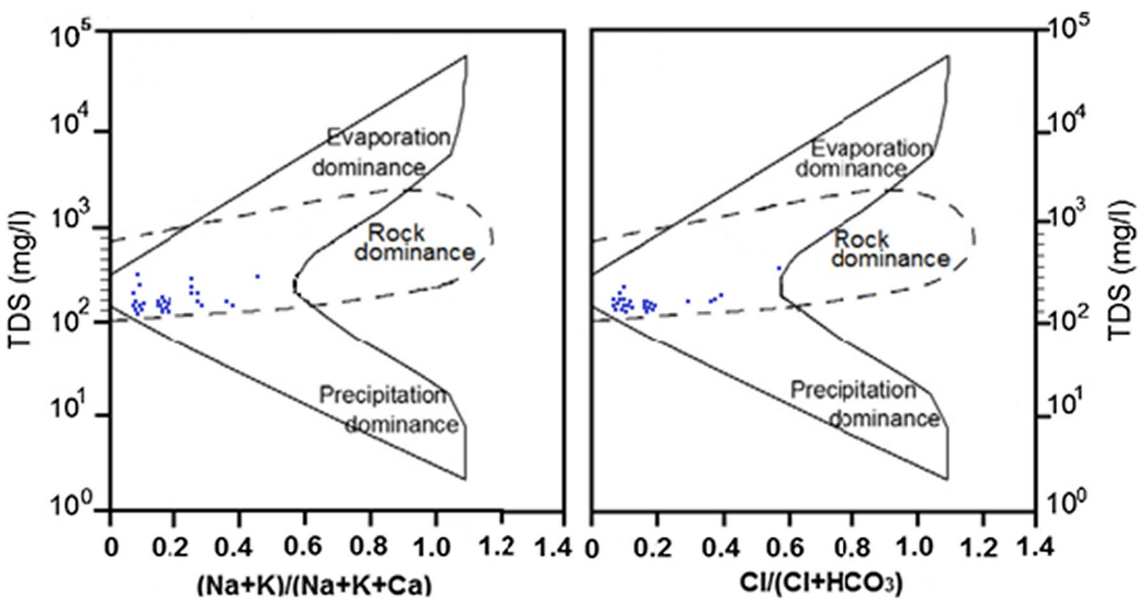

Fig. 4 Gibbs ratio for groundwater in post-monsoon

Hydrochemical facies

The evolutionary aspects of water resources can be known by the hydrochemical diagrams. Along with groundwater quality distribution and the sections of hydrochemical aspects of water samples give a broad spectrum of the water characteristics of the study area. Here, the chemical processes due to mixing with the lithological units are shown aptly through the facies, and the graphical representation makes it easy to comprehend (Todd 1980).

Hill–Piper trilinear diagram

Hill–Piper trilinear diagram was used to plot the results of water analysis and to get an idea about the hydrochemical regime of resources of groundwater in the research area (Piper 1944) (Figs. 5, 6). Differences and similarities among the analysed water samples are clearly demarcated in the Piper–Hill diagram as the plotted together water samples in the diagram are of similar hydrochemical properties and those which are scattered are of different

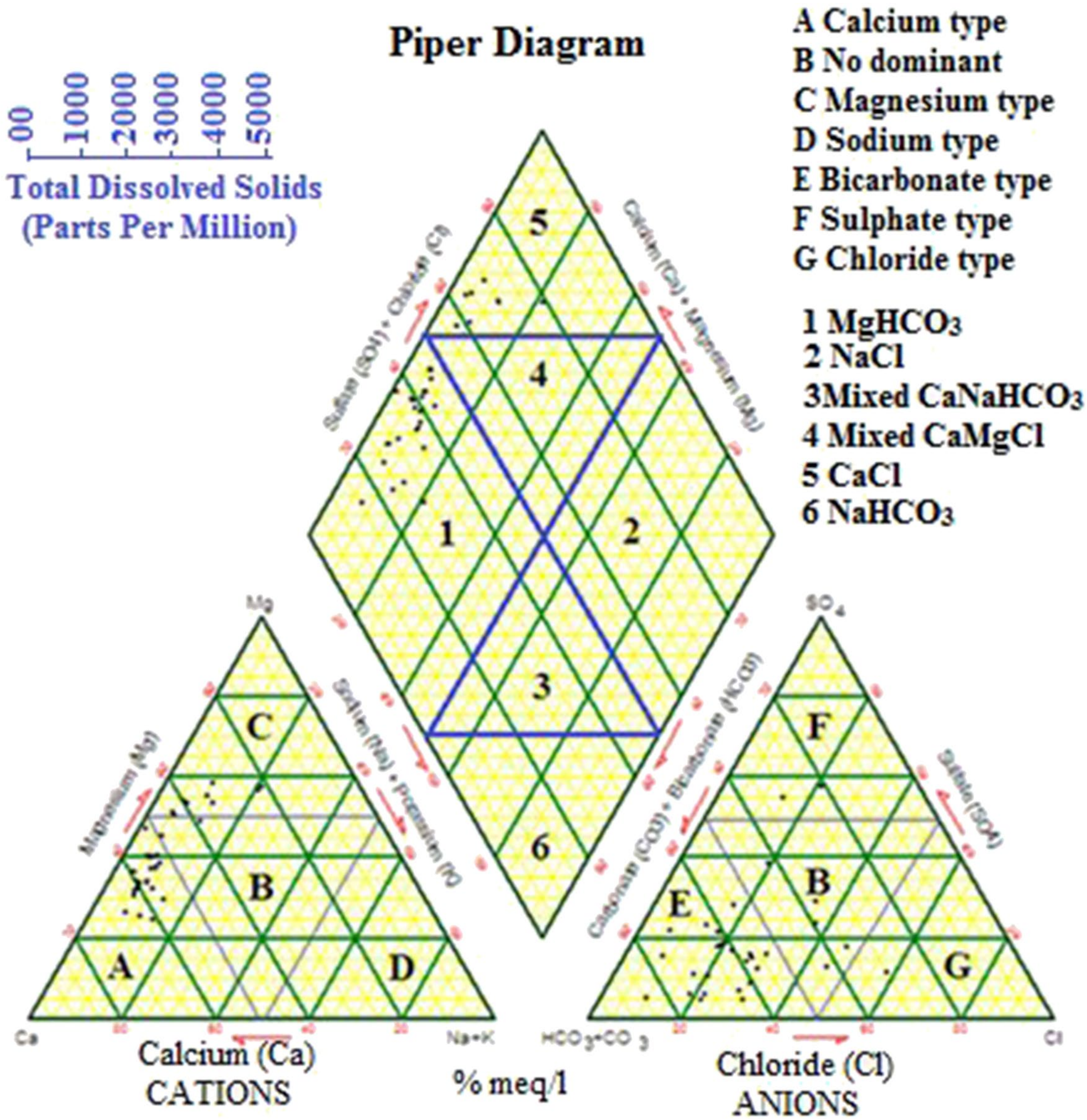

Fig. 5 Piper classification diagram illustrating the chemical composition of groundwater in pre-monsoon

properties. The chemical relationships among water samples are starkly represented through this diagram (Walton 1970). Three well-defined fields are depicted in the Hill diagram which consists of triangular fields consisting of two in number and a one centrally located diamond-shaped field. Per cent milliequivalent per litre (% meq/l) is the unit used for various values plotted on the diagram. The central diamond-shaped field is the region where the total characteristics of water samples are shown.

On the basis of the Piper diagram, the cation plot clearly shows that Ca^{2+} ion dominates the groundwater composition (with 66.6% and 50%) in pre- and post-monsoon seasons, while there is a significant number of samples falling in the no dominant cation zone (i.e. 6.6% and 16.6%) in both pre- and post-monsoon seasons, respectively. Along with coming to the case of anions, the dominant role is played by bicarbonate ions with 73.3% dominance in pre-monsoon and 66.6% in post-monsoon seasons, respectively, also with 16.6% and 13.3% samples falling in the no dominant anion zone. Recharge zone is classified when the dominant ion is HCO_3^- in the analysed water samples (Ophori and Toth 1989a, b; Rao 2007). Also, if we see the zone of Ca^{2+}–Mg^{2+}–HCO_3^- water type then 70% in pre-monsoon and 20% in post-monsoon seasons fall in the above-mentioned water types, while if we take the Mg^{2+}–HCO_3^- water type with

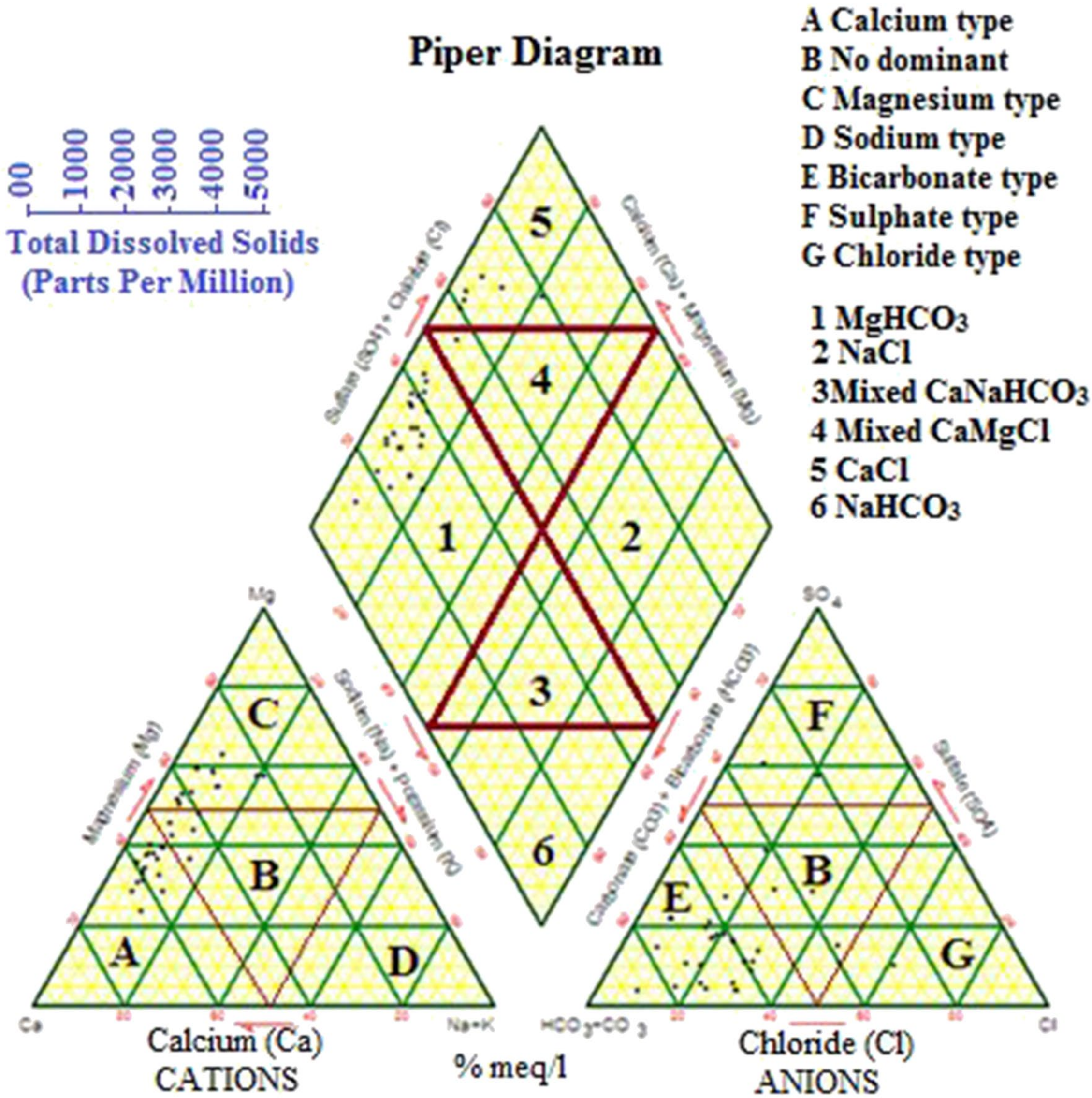

Fig. 6 Piper classification diagram illustrating the chemical composition of groundwater in post-monsoon

secondary salinity water samples are exceeding 50% and with this type which shows ion-exchange both inverse or reverse, which are the reasons for controlling the chemistry of groundwater (Davis and Dewiest 1966). However, the rest of water samples that is 26.6% in pre-monsoon and 20% in post-monsoon seasons are falling in Ca^{2+}–Mg^{2+}–Cl^{-}–SO_4^{2-} type simultaneously showing Ca^{2+}–Mg^{2+}–Cl^{-} facies type where the dominant hydrochemical facies for either cation or anion cannot be deciphered clearly for both seasons (Todd and Mays 2005), while in the case of Ca^{2+}–Mg^{2+}–Cl^{-} water type, one sample falls in this category but only in the post-monsoon season which runs parallel with the post-tourist season. The Ca^{2+}–Mg^{2+}–Cl^{-} type of water and calcium chloride type of hardness is denoted where non-carbonate hardness of water exceeds more than 50% in estimation.

As per Hill–Piper diagram, it can be rightly said that the groundwater of the study area is falling in the category of Ca^{2+}–Mg^{2+}–HCO_3^{-} type and mixed type that is Ca^{2+}–Mg^{2+}–Cl^{-}. As per the results of water-type classification, the natural environment of the concerned area plays an important role in dissolution of the major ions. Categorization of groundwater samples based on different facies is shown in Table 5.

Table 5 Groundwater samples characterization based on Piper diagram

Class	Groundwater types corresponding sub-divisions of facies	Samples in the different categories	
		Pre-monsoon	Post-monsoon
		No. of samples (%)	No. of samples (%)
A	Calcium type	20 (66.6)	15 (50)
B	No dominant (cations)	2 (6.6)	5 (16.6)
C	Magnesium type	9 (30)	10 (33.3)
D	Sodium type	NIL	NIL
E	Bicarbonate type	22 (73.3)	20 (66.6)
B	No dominant (anions)	5 (16.6)	4 (13.3)
F	Sulphate type	2	2
G	Chloride type	1 (3.3)	1 (3.3)
1	HCO_3^-–CO_3^{2-} and Ca^{2+}–Mg^{2+} (temporary hardness); magnesium bicarbonate type (carbonate hardness exceeds 50%)	21 (70)	20 (66.6)
2	Cl^-–SO_4^{2-} and Na^+–K^+ (saline); sodium chloride type (non-carbonate alkali exceeds 50%)	NIL	NIL
3	Mixing Zone (Ca^{2+}–Na^+–HCO_3^-); base ion-exchange processes	NIL	NIL
4	Mixing Zone (Ca^{2+}–Mg^{2+}–Cl^-); reverse ion-exchange processes	NIL	1 (3.3)
5	Cl^-–SO_4^{2-} and Ca^{2+}–Mg^{2+} (permanent hardness); calcium chloride type (non-carbonate hardness exceeds 50%)	8 (26.6)	6 (20)
6	HCO_3^-–CO_3^{2-} and Na^+–K^+ (alkali carbonate); sodium bicarbonate type (carbonate alkali exceeds 50%)	NIL	NIL

Correlation matrix for analysed parameters of groundwater

In independent and dependent variables, their extent of closeness is measured by the statistical coefficient known as correlation coefficient. When one parameter increases, the corresponding parameter increases, also termed as positive correlation, and when one parameter decreases, simultaneously the corresponding parameter decreases, also termed as negative correlation and this can be described as direct correlation relationship. The value ranges from +1 to −1 as correlation coefficient (r). When the correlation is in range of +0.8 to +1.0 and −0.8 to −1.0, then such a relation is termed as strong. It is termed as weak when the range is from 0.0 to 0.5 and −0.0 to −0.5. Matrix for correlation for groundwater is shown in Tables 6 and 7 for pre-monsoon and post-monsoon seasons.

- The matrix of correlation during pre-monsoon seasons shows a strong correlation of EC with TDS ($r = 0.96$). All the dissolved solids particularly known as mineral salts in water are denoted by TDS. The higher conductivity

Table 6 Correlation matrix for groundwater samples (pre-monsoon)

Parameters	Ph	EC	TDS	TH	Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3^-	Cl^-	NO_3^-	SO_4^{2-}
pH	1.00											
EC	0.23	1.00										
TDS	0.32	**0.84**	1.00									
TH	0.28	0.20	0.26	1.00								
Ca^{2+}	0.14	−0.42	−0.32	**0.60**	1.00							
Mg^{2+}	0.24	**0.61**	**0.58**	**0.53**	−0.15	1.00						
Na^+	0.33	**0.63**	**0.60**	0.24	−0.29	**0.52**	1.00					
K^+	0.38	0.08	0.18	0.22	0.22	0.02	0.37	1.00				
HCO_3^-	0.46	0.12	0.23	0.21	0.08	0.13	**0.58**	0.36	1.00			
Cl^-	−0.02	0.15	0.21	0.35	0.38	0.00	0.23	0.34	0.21	1.00		
NO_3^-	0.28	−0.15	−0.12	−0.25	0.03	−0.27	−0.18	**0.50**	−0.06	0.02	1.00	
SO_4^{2-}	0.34	0.00	−0.02	0.26	0.22	0.22	0.28	0.17	0.30	0.11	0.30	1.00

The highlighted or bold ones are those which are above 0.5 which have some correlation level and rest below 0.5 which have very low or negligible correlations are not highlighted

Table 7 Correlation matrix for groundwater samples (post-monsoon)

Parameters	pH	EC	TDS	TH	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^-	Cl^-	NO_3^-	SO_4^{2-}
pH	1.00											
EC	0.09	1.00										
TDS	−0.01	**0.96**	1.00									
TH	−0.13	0.13	0.12	1.00								
Ca^{2+}	−0.12	−0.35	−0.36	0.67	1.00							
Mg^{2+}	0.09	**0.60**	**0.54**	0.44	−0.18	1.00						
Na^{+}	0.03	**0.60**	**0.60**	0.19	−0.25	0.45	1.00					
K^{+}	−0.31	−0.03	0.01	0.22	0.30	−0.09	0.35	1.00				
HCO_3^-	0.26	0.14	0.12	0.17	0.01	0.11	**0.61**	0.30	1.00			
Cl^-	−0.04	0.14	0.19	0.33	0.27	−0.05	0.27	0.29	0.22	1.00		
NO_3^-	−0.27	−0.18	−0.20	−0.26	0.05	−0.35	−0.23	0.46	−0.12	−0.07	1.00	
SO_4^{2-}	−0.08	0.02	−0.02	0.30	0.28	0.19	0.30	0.25	0.29	0.04	0.18	1.00

The highlighted or bold ones are those which are above 0.5 which have some correlation level and rest below 0.5 which have very low or negligible correlations are not highlighted

values of water correspond with more amounts of dissolved minerals in the water body.

- The strong correlation of EC and TDS with Mg^{2+} ($r=0.61$ and $r=0.58$) and Na^+ ($r=0.63$ and $r=0.60$) indicates the major cations controlling the water chemistry.
- There also exists a correlation which is positive between TH with Ca^{2+} ($r=0.60$) and Mg^{2+}($r=0.53$), indicating the same origin and the major source of hardness in water mainly due to the salts like $CaCO_3$ and $MgCO_3$ (Herojeet et al. 2016).
- The significant correlation between Mg^{2+} with Na^+ ($r=0.52$) and Na^+ with HCO_3^- ($r=0.58$) shows processes of various ion-exchanges, and rock minerals are naturally weathering in the aquifer system. The correlation of HCO_3^- with Na^+ relates to natural processes, whereas NO_3^- with K^+ has to be related with human-induced activities (Srivastava and Ramanathan 2008; Okiongbo and Douglas 2015).
- In post-monsoon season, the correlation matrix shows that correlation is positive between EC and TDS with correlation coefficient (r) 0.96. Both TDS and EC have a correlation which is positive with Mg^{2+} ($r=0.60$ and 0.54) and Na^+ ($r=0.60$ and 0.60), indicating weathering of bedrocks minerals.

Suitability of groundwater for irrigation

1. Water is an easily assessable resource where human being is utilizing it for different purposes depending on their necessity. The process of irrigation causes recharging of water present in the soil of root zone of the plants. In this process, source of water is due to human intervention rather than the natural media of precipitation in the form of rainfall and snowfall. For every variation in water usage, it is required that it meets the optimum quality of water, and the techniques and methods for water quality analysis should be of the standard and well-tested methodologies (Babiker 2007). Irrigation water quality varies substantially depending principally upon the salinity, soil permeability, toxicity and some miscellaneous concerns such as loading of excessive amounts of nitrogen or if the variation of pH of water is unusual like very abrupt increase or decrease. The important factor for elucidating the irrigation quality of water is the chemical quality of water (Gupta 1989). The extent of suitability of water for irrigation purposes is determined by the composition and concentration of its constituents dissolved in it. On both soils and plants, irrigation suitability is dependent on some major constituents of minerals dissolved in that water (Wilcox 1955a, b). Some parameters which determine the suitability for irrigation of 30 groundwater samples are determined by (1) (EC) Electrical conductivity, (2) (SAR) sodium adsorption ratio, (3) US salinity diagram (4) (%Na) per cent sodium, (5) (RSC) residual sodium carbonate, as shown in Table 8.

Classification on four irrigation parameters is shown in Table 9 which shows that:

(1) *Electrical conductivity* Total dissolved solids (TDS) or total dissolved ions is measured by (EC) electrical conductivity of the given water media. One of the major concerning factors for determining irrigation quality of water is its concentration of excessive salt content. If the soil and climatic conditions along with regular

Table 8 Irrigation quality parameters for groundwater

S. no.	Location	Pre-monsoon				Post-monsoon			
		EC	SAR	%Na	RSC	EC	SAR	%Na	RSC
1	Gyalung	223	1.03	10.13	−2.64	220	1.00	10.70	−2.53
2	Gangles	210	1.31	9.33	−3.93	190	1.30	8.88	−4.00
3	Gompa	283	1.12	11.25	−3.43	260	1.10	11.72	−3.35
4	Sankar	205	0.99	12.76	−2.30	201	0.97	12.94	−2.36
5	Yourtung	234	1.47	7.44	−4.84	220	1.43	7.73	−4.61
6	Khagshal	256	1.71	13.89	−2.87	270	1.63	14.76	−2.70
7	Changspa	287	1.19	8.64	−3.67	280	1.12	8.28	−3.52
8	Chubi	248	1.20	18.80	−1.21	220	1.09	21.41	−0.80
9	LEDeG	275	1.11	8.57	−2.87	262	1.01	9.61	−2.46
10	Karzoo	303	1.10	9.64	−3.12	300	1.02	10.04	−2.83
11	U.Tuckha	439	0.98	10.23	−1.17	400	0.93	9.72	−1.12
12	Middle Sch	387	1.57	6.19	−5.13	340	1.63	6.33	−5.34
13	Fort Road	549	1.54	9.22	−4.41	529	1.58	8.69	−4.72
14	Shenam	324	1.28	10.60	−3.39	365	1.32	9.76	−3.63
15	16BRTF	295	1.30	18.20	−1.87	286	1.22	18.18	−1.67
16	Zorawar Ft	424	1.23	12.05	−2.64	387	1.18	11.68	−2.57
17	Skara Spring	575	1.37	15.58	−3.47	556	1.34	14.88	−3.45
18	Skalzangling	403	1.15	15.45	−2.63	390	1.16	15.55	−2.64
19	Housing Cl	849	1.68	17.34	−4.24	826	1.53	17.04	−3.92
20	DIHAR	660	1.43	15.55	−2.80	568	1.38	14.88	−2.69
21	Murtse	357	1.18	10.44	−3.19	360	1.22	10.21	−3.34
22	Ibex Colony	423	1.32	8.45	−4.04	411	1.22	8.47	−3.69
23	ITBP Leh	351	1.57	9.98	−3.50	302	1.53	9.68	−3.39
24	MES IIIrd	347	1.25	8.21	−2.79	321	1.19	8.17	−2.66
25	MES Spituk	482	1.53	11.17	−3.29	461	1.40	11.39	−2.80
26	Airforce Stn	200	1.20	9.70	−2.68	210	1.24	9.75	−2.85
27	CIBS	301	1.63	7.95	−4.14	501	1.53	9.05	−3.60
28	Zivey Tsal	835	1.81	30.06	−1.81	820	1.67	28.72	−1.66
29	Choglamsar	496	1.68	18.34	−2.44	488	1.53	18.42	−1.96
30	SOS Village	367	1.49	2.76	−3.29	356	2.02	18.00	−3.09

cultural practices remain stagnant regarding irrigation practices, a higher measure of EC will result in a higher rate of salinity hazard for the growing crops. The EC of irrigation water is often denoted as EC*w*.

Out of total 30 samples, 20% lie in excellent quality during both pre-monsoon and post-monsoon seasons, while 73.3% samples of water lie in good quality during both pre-monsoon and post-monsoon seasons. The remaining 6.6% samples fall in fair category. The absorption of nutrients and water from the soil is interrupted due to high level of EC as a result of reduction in the general osmotic activity level of plants growing in such irrigated water (Saleh et al. 1999).

(2) (*Sodium adsorption ratio*) *SAR* All 100% samples that is total 30 samples of groundwater lie in excellent quality during both pre-monsoon and post-monsoon seasons.

Sodium Hazard is expressed in terms of sodium adsorption ratio (Gholami and Srikantaswamy 2009). The hazard or danger due to excessive concentration of sodium ions is estimated by sodium adsorption ratio (SAR). The suitability of water for irrigation purposes is determined by SAR, and this value is evaluated by ratio of Na^+ ions concentration over square root sum of Ca^{2+} and Mg^{2+} ions concentration divided by 2 in a sample of water. The SAR equation (Hem 1991) is mentioned hereunder:

$$\mathrm{SAR} = \frac{\mathrm{Na}^+}{\left(\sqrt{\frac{\mathrm{Ca}^{2+}+\mathrm{Mg}^{2+}}{2}}\right)} \quad \text{(all units in meq/l)}$$

If the concentration of Na^+ ions is high and Ca^{2+} ions is low, then Na^+ ions gets filled up in the complex of ion-exchange, and ultimately the structure of soil gets

Table 9 Different criteria of water suitability for irrigation purposes

S. no.	Parameters	Values	Water class	Groundwater	
				No. of samples (percentage of samples)	
				Pre-monsoon	Post-monsoon
1.	EC (μS/cm) (USSL 1954)	< 250	Excellent	6 (20)	6 (20)
		250–750	Good	22 (73.3)	22 (73.3)
		750–2250	Fair	2 (6.6)	2 (6.6)
		> 2250	Poor	NIL	NIL
2.	SAR (Todd 1959)	10	Excellent	30 (100)	30 (100)
		10–18	Good	NIL	NIL
		18–26	Doubtful	NIL	NIL
		> 26	Unsuitable	NIL	NIL
3.	% Na (Wilcox 1955)	< 20	Excellent	29 (96.6)	28 (93.3)
		20–40	Good	1 (3.3)	2 (6.6)
		40–60	Permissible	NIL	3 (5)
		60–80	Doubtful	NIL	NIL
		> 80	Unsuitable	NIL	NIL
4.	RSC (meq/l) (Eaton 1950)	< 1.25	Water can be used safely	30 (100)	30 (100)
		1.25–1.5	Can be used with management	NIL	NIL
		> 2.5	Unsuitable for better yields	NIL	NIL

destroyed as the clay particles in the soil content gets dispersed (Todd 1980). So, the growth ability of plants is eventually affected.

(3) US salinity diagram

Another valid measure to fathom salinity hazard is the level of conductance. The osmotic activity of plants reduces with the increasing salinity gradient of soil where it grows (Subramani et al. 2005). In simpler terms, the plants are not able to absorb as much water which is required due to the presence of large concentration of ions in soil which retains the irrigated water. So, ultimately the water available or required for the plants reduces. With respect to EC and SAR values, the US Salinity Laboratory (USSL) classification of groundwater was undertaken for 30 groundwater samples (Table 9). According to the 30 groundwater samples of study area after plotting it on the USSL diagram, both during pre-monsoon and post-monsoon seasons, during the season of pre-monsoon, six samples lie in the field of C1S1, two samples in C3S1, while the rest 22 samples in C2S1. Accordingly during post-monsoon season, three samples lie in C1S1 field, two samples in C3S1 field and the rest 25 samples in C2S1 field (Fig. 7). Hence, quality of water in the area concerned is satisfactory for the purpose of irrigation use in almost all soil types with a slight chance of developing harmful levels of exchangeable sodium.

(4) *Per cent sodium* (*%Na*) With respect to calcium and magnesium ions concentration, if the concentration of Na^+ ions is in excess, there occurs reduction in the level of permeability of soil. This occurs due to absorption of Na^+ ions by clay particles instead of Mg^{2+} ions and Ca^{2+} ions, thus inhibiting supply of water required for the crops. Calcium and magnesium have the tendency to flocculate the soil particles rendering looseness in the soil and enhance good penetration of water and air. On the other hand, sodium causes deflocculation and prevents free movement of water. The sodium percentage (%Na) is calculated using the following formula given by Wilcox (1955a, b):

$$\%\mathrm{Na} = \frac{\mathrm{Na}^+ + \mathrm{K}^+}{\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+} + \mathrm{Na}^+ + \mathrm{K}^+} * 100 \quad \text{(all units in meq/l)}$$

Against the values of EC in Wilcox diagrams, the calculated values of groundwater for %Na in the area are plotted (Fig. 8)

According to this parameter, 96.6% and 93.3% samples out of total 30 groundwater samples during pre- and post-monsoon seasons, respectively, lie in excellent quality of water, while the remaining 3.3% and 6.6% during pre- and post-monsoon seasons, respectively, lie in good quality of water. Thus, all samples of groundwater lie in purview of water quality which is excellent to good and are fit for purposes of irrigation.

(5) *Residual sodium carbonate* (*RSC*) The suitability of water for purposes of irrigation is dependent on many factors, one vital phenomenon being the increase in

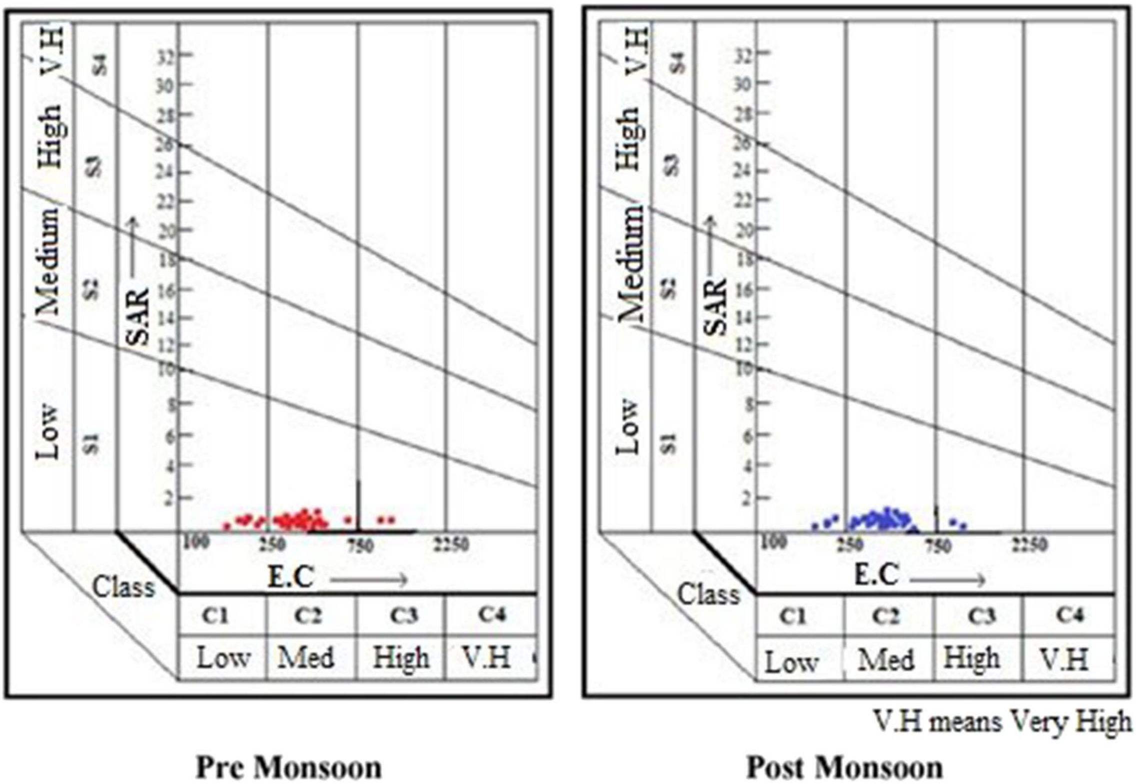

Fig. 7 USSL classification of groundwater in the study area

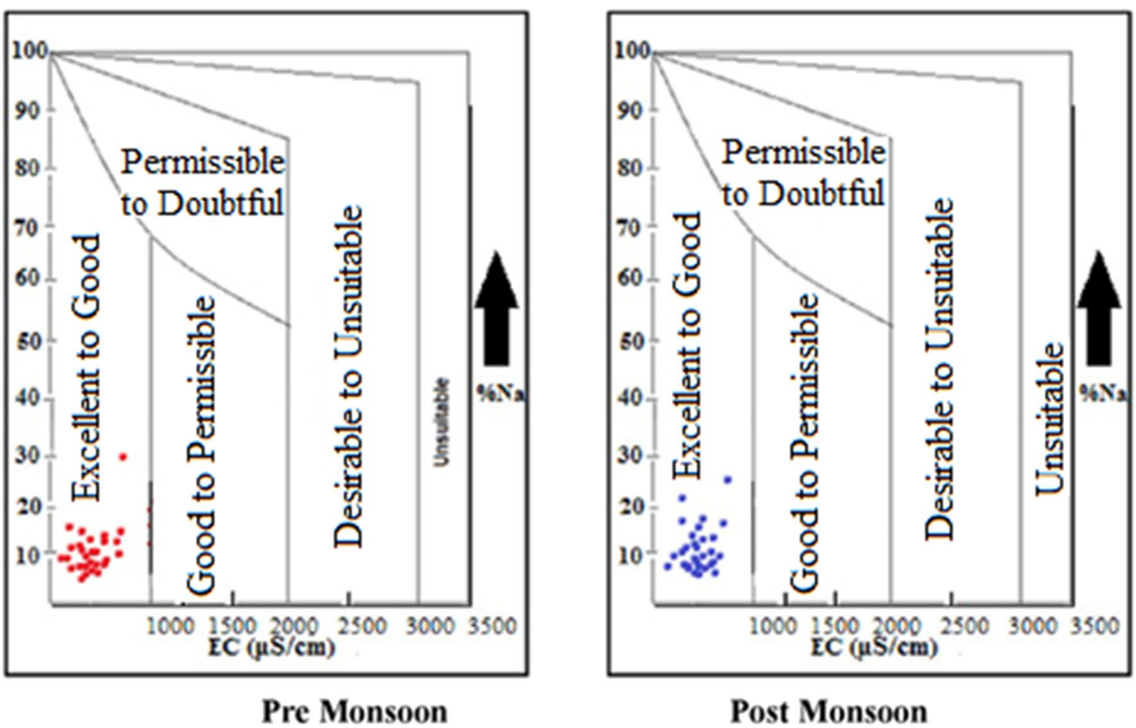

Fig. 8 Wilcox diagram of groundwater in the study area

concentration of carbonate ions and bicarbonate ions over the total sum of concentration of magnesium ions and calcium ions. When the water meant for irrigation uses has HCO_3^- ions and CO_3^{2-} ions in excess, then this alkaline water has an affinity for the ions of Ca^{2+} ions and Mg^{2+} ions to undergo precipitation, as the concentration levels of irrigation water in soil increase. Irrigation water with high RSC is regarded deleterious towards the physical attributes of soils, as it decreases the overall soil permeability. Eventually, the level of sodium increases in form of sodium carbonate and this is denoted by RSC which is evaluated by the equation (Eaton 1950):

$$\text{RSC} = \left(\text{CO}_3^{2-} + \text{HCO}_3^-\right) - \left(\text{Ca}^{2+} + \text{Mg}^{2+}\right) \quad \text{(all units in meq/l)}$$

Out of total 30 groundwater samples, all 100% lie in excellent quality during pre-monsoon and post-monsoon seasons.

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