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ORIGINAL ARTICLE

Groundwater quality issues and management in Ramganga Sub-Basin

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Abstract Groundwater quality receives increasing attention in water management in India. The purpose of this paper is to highlight the emerging issues of groundwater quality in the Ramganga Sub-Basin (RSB), a tributary joining the Ganga River from the northern plains, which extends over 30,839 Sq. km and covers 15 districts in both Uttarakhand and Uttar Pradesh. The groundwater in most of the districts of the RSB has high concentration of nitrate, iron, salinity and fluoride, which exceed the standards prescribed for drinking water by the Bureau of Indian Standards (BIS) and World Health Organization (WHO). Arsenic contamination in groundwater is an emerging issue in few groundwater development blocks. Moreover, groundwater with substantial hardness, high sulfate, and high manganese is emerging issue in some districts. Additionally, shallow aquifers have high concentration of ions. In the RSB, the quality of groundwater, especially in the shallow aquifers, is influenced by the contamination of poor quality surface water, due mainly to poor sanitation, improper disposable of domestic sewage water, manures and irrigation return flows. To reduce deterioration of water quality further, the RSB requires proper sanitation facilities, efficient usage of agrochemicals, as well as an awareness program of water-related disease.

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Introduction

Groundwater quality is one of the key components in groundwater management. Availability and suitability of groundwater for various uses are inseparable parameters. In many countries, good quality groundwater is not available for human consumption (Gleick 2000). Generally, groundwater quality is largely influenced by the aquifer materials and geochemical processes. Diverse geological formations and climatic conditions affect the chemical properties of groundwater. Additionally, the shallow unconfined aquifer is vulnerable to contamination from surface water resources, as well as recharge of wastewater from land surface. Once the aquifer is contaminated, the time required for recovery through natural processes is very long and the remedial actions are expensive. This is the case in much of the Eastern Ganges Basin (Rajmohan and Prathapar 2013, 2014).

Groundwater contamination processes are classified into geogenic and anthropogenic. Geogenic processes namely dissolution, precipitation, hydrolysis, adsorption/desorption, ion exchange, oxidation, reduction and biochemical-mediated reactions regulate groundwater quality (Matthess 1982; Rajmohan and Elango 2004). Contaminants such as arsenic, iron, selenium and radon are generally formed by geogenic processes, and some of these contaminants exist in groundwater in the Ganges River Basin (BGS and DPHE 2001; Bhattacharya et al. 2003; Saha et al. 2009; CGWB 2014; Rajmohan and Prathapar 2013, 2014; Shah 2014). Nitrates, nitrites, ammonium, phosphates, chloride, heavy metals and bacteria are mostly originated by the anthropogenic processes such as dumping sites, industrial wastewater and lagoons, fertilizers, manure and pesticides in agricultural practices, septic tanks, cesspools, domestic sewage lines and urban wastewater releases (Raju et al. 2009; Khan et al. 2015). However, recharge from monsoon rain and the associated floods flush the vadose zone and dilute the groundwater to reduce the solute load (Rajmohan and Elango 2005, 2006). Generally, aquifer materials act as a filter for several contaminants, especially biological contaminants (Dash et al. 2008; Juhasz-Holterman et al. 1998; Medema and Stuyfzand 2002). However, they may not attenuate toxic metals efficiently, because the extent of removal of toxic metals depends on the metal concentrations in the source water and retention properties of aquifer materials.

In the Ganges basin, the Quaternary alluvial deposits act as a source of water for the domestic and irrigation sectors and also to support socioeconomic development (Singh 1987; CGWB 2014a, b). Hence, a detailed knowledge about the quality of groundwater is necessary to implement a successful water management plan (United Nations 2015). This paper evaluates the district-wise groundwater quality issues in Ramganga Sub-Basin (RSB) and provides the overall scenario through the analysis of data collected from the public domain. This study can support future research related to groundwater quality, development and management in the RSB. To the authors' knowledge, this is the first paper that explains the district-wise groundwater quality of whole Ramganga Sub-Basin.

Study region

The Ramganga Sub-Basin (RSB) lies between 78°14′ to 80°8′ and 27°7′ to 30°6′ in India (CWC/NRSC 2014, Fig. 1). The topographic elevation of the Ramganga Sub-Basin varies from 1000 to 2688 m above mean sea level (amsl) in the northern part. In the plains, the topography ranges from 360 m in Bijnor district to 124 m in Hardoi district in the south. The Ramganga River originates from the lower Himalayas (about 3110 m above mean sea level) near the Lohba village, Garhwal district, Uttarakhand, and it is one of the important tributaries in the Ganga River. The river flows through the states of Uttarakhand (formerly Uttaranchal) and Uttar Pradesh (UP) and has a total length of 595 km (Water Resources Information System of India [http://www.india-wris.nrsc.gov.in]). The RSB covers around 30,839 Sq. km. In this basin, 15 districts in both Uttarakhand (Almora, Chamoli, Garhwal, Nainital and U.S.Nagar) and Uttar Pradesh (Badaun, Bareilly, Bijnor, Farrukhabad, Hardoi, Jyotiba Phule Nagar (J.P. Nagar), Moradabad, Pilibhit, Rampur and Shahjahanpur) are located (Fig. 1). The climate of this region is subtropical monsoon climate. During summer, it is dry and hot and

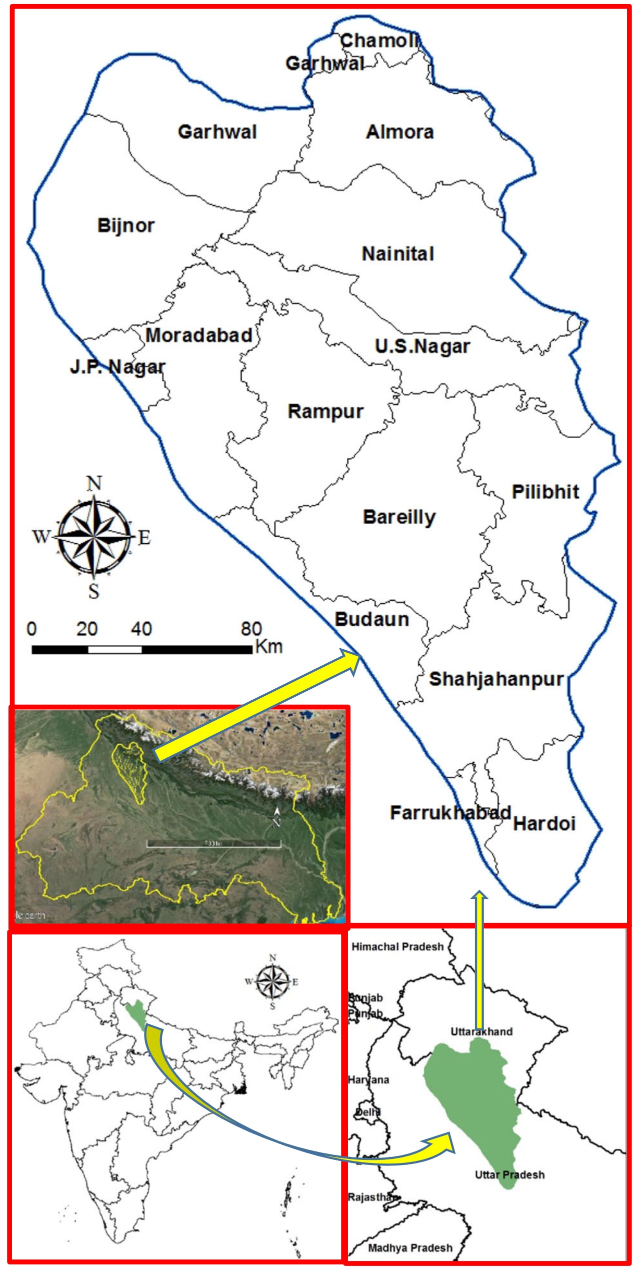

Fig. 1 *Map* showing the Ramganga Sub-Basin districts

winter is moderate to severe cold. In the RSB, the average annual rainfall from 1996 to 2010 was 923 mm, with a minimum of 506 mm (in 1997) to a maximum of 1221 mm (in 1998). The basin receives 90 % of the rainfall during monsoon from July to September.

Hydrogeologically, Uttarakhand is divided into two distinct hydrogeological regimes, namely the Gangetic alluvial plain and the Himalayan mountain belt (CGWB 2014a, b). The Gangetic alluvial plain is covered by alluvium and unconsolidated sedimentary material of varying fractions and zones of groundwater development. The Himalayan mountain belt is covered by a hilly region and has less groundwater potential. Groundwater occurs mostly in fissures/fractures in this formation. In Siwalik formations, the yield of tube wells ranges from 50.4 to 79.2 m^3/h, but in Bhabar formations it is up to 332.4 m^3/h. In the Tarai belt, the yield of tube well varies from 36 to 144 m^3/h. In the Indo-Gangetic plain, it is between 90 and 198 m^3/h (CGWB 2014a, b).

Hydrogeologically, Uttar Pradesh is divided into five units, namely Bhabar, Tarai, Central Ganga plains, Marginal alluvial plains and Southern Peninsular zone. The yield of tube wells tapping in Bhabar and Tarai zones varies from 100–300 to 100–200 m^3/h, respectively. Generally, auto-flow conditions (Piezometric head 6–9 m above ground level) are observed in Tarai region like Uttarakhand, whereas the water table is deeper in Bhabar region. In the Central Ganga plain, four major aquifers are identified with the depth range of 700 mbgl and the yield of the tube wells varies from 90 to 200 m^3/h (CGWB 2014a, b).

Field observations show that the groundwater table in RSB ranges between 1.5 and 4.9 mbgl in the upstream districts (U.S. Nagar and Bijnor) and gradually becomes shallow in the downstream (Hardoi and Farrukhabad districts). In the downstream area, the depth to groundwater varies from 0.6 to 1.8 mbgl. The depth of the wells ranges from 7.6 to 45.7 mbgl. In this basin, a multilayered aquifer is identified and potential aquifers are 7.6–18.3 mbgl and 30.5–45.7 mbgl. Most of the wells are installed in these two aquifers. Government hand pumps are installed in the deeper aquifer, and the depth of the hand pumps ranges between 33.5 and 45.7 mbgl. Household hand pumps are mostly tapping in the shallow aquifer. In the RSB, major cropping pattern in the upstream areas are maize and sugar cane, whereas downstream the priority is paddy and sugar cane. The surface water irrigation is practiced along and near the canals and streams. The RSB mostly depends on groundwater for irrigation and domestic purposes.

Methodology

Groundwater quality data were obtained from the Ministry of Drinking Water and Sanitation, Government of India Web site (NRDWP 2014). The water quality parameters are classified into mandatory (pH, TDS, Alkalinity, Cl, NO_3, F, As and Fe) and non-mandatory (total hardness (TH), turbidity, Ca, Mg, SO_4, Al, Cu, Mn, residual chloride, coliform and *Escherichia coli*). Non-mandatory parameters are infrequently monitored and not analyzed for all the samples. Data sets of all the parameters were downloaded from the Web site (NRDWP 2014), and data cleaning was carried out, especially for incomplete data, typing errors, number of samples analyzed for particular parameters, etc. The water quality parameters of the cleaned data are then selected for statistical analysis and subsequent discussion.

Although many parameters are reported on the Web site (NRDWP 2014), water samples are not analyzed for all the parameters, especially those of the non-mandatory group. Based on the available data, TH, TDS (salinity), NO_3, SO_4, Fe, F and As are selected for further analysis. The data were analyzed using MS-Office and Statistical Package for Social Sciences (SPSS, v.16.0). ArcGIS (v. 10.2.2) software is used to prepare location as well as parameters distribution maps. In the database, location coordinates for sampling wells are not available to demarcate the contamination zones and to prepare spatial maps of individual parameters. Table 1 illustrates the district-wise descriptive statistics of the selected water quality parameter.

Results and discussion

Groundwater in the Ganges basin is severely affected by arsenic, fluoride, nitrate, chloride and salinity (CGWB 2014a, b). Similar observations are reported in RSB as well. Table 1 shows the descriptive statistics of selected parameters namely pH, TDS (salinity), TH, Cl, SO_4, NO_3, F, As and Fe due to data availability. In the RSB, groundwater pH varies from 6.2 to 9 with an average of 7.4 ($n = 23{,}216$). Except for a few wells, the groundwater pH is within the permissible range (6.5–8.5) prescribed by the BIS and WHO for drinking water. Groundwater in the RSB districts is slightly acidic to alkaline in nature.

Salinity

Salinity is one of the important parameters that decides the suitability of groundwater for irrigation, domestic and drinking uses. High-salinity water generally damages crops and reduces plant growth and yield. In the RSB, most of the districts have high salinity in groundwater (Fig. 2; Tables 1, 2). The total dissolved solids (TDS) range from 100 to 2000 mg/l with a mean value of 494 $\pm$ 219 (Mean $\pm$ SD) mg/l ($n = 21{,}942$). The average TDS value in Bareilly, Bijnor and Hardoi districts are greater than 500 mg/l (Table 1). In addition, the percentage of groundwater samples with TDS $>$ 500 mg/l are more in Bareilly (93 %), Hardoi (75 %), Bijnor (61 %), Budaun (40 %) and Shahjahanpur (14 %) districts (Table 2). Moreover, 14 % of groundwater samples have TDS $>$ 1000 mg/l in Bareilly district. According to WHO (2011) and BIS (2012), groundwater with TDS $\leq$ 500 mg/l is suitable for drinking and it may be extended to 1000 mg/l in case of no alternative sources. Beyond this limit, water is not palatable. Groundwater with high salinity is

Table 1 District-wise statistical summary of selected physicochemical parameters in groundwater, RSB *Data source:* NRDWP (2014)

District name	Stat	pH	TDS	TH	Cl	SO_4	NO_3	As	F	Fe
Uttar Pradesh state										
Bareilly	Min	6.5	200	100	15	19	1.3	0.01	0.02	0.02
	Max	8.5	2000	600	1100	400	85.0	0.30	1.50	1.00
	Average	7.1	865	344	409	221	44.9	0.04	1.10	0.41
	StdDev	0.5	323	63	163	64	1.8	0.05	0.30	0.23
	Count	1526	2606	2612	2567	2555	2391	32	2611	2516
Bijnor	Min	6.5	124	100	15	14	1.3	NA	0.10	0.10
	Max	8.5	1010	580	400	320	886	NA	18.0	8.20
	Average	7.9	529	263	31	30	6.1	NA	0.42	0.39
	StdDev	0.5	84	52	15	14	18.6	NA	0.34	0.30
	Count	3426	3507	3524	3397	3360	3444	NA	3525	3524
Budaun	Min	6.5	100	80	25	100	1.0	NA	0.05	0.01
	Max	8.5	1310	580	780	600	245	NA	75.0	7.00
	Average	7.5	473	301	188	249	19.8	NA	0.6	0.18
	StdDev	0.4	219	86	133	56	9.6	NA	2.2	0.18
	Count	2161	1902	2114	2191	2170	2175	NA	2123	1927
Farrukhabad	Min	6.6	NA	135	100	NA	10.0	NA	0.30	0.10
	Max	8.2	NA	380	300	NA	30.0	NA	1.30	2.00
	Average	7.6	NA	239	217	NA	11.7	NA	0.55	0.18
	StdDev	0.3	NA	46	46	NA	2.8	NA	0.18	0.09
	Count	746	NA	747	748	NA	752	NA	752	751
Hardoi	Min	6.9	130	56	10	6	1.2	NA	0.10	0.03
	Max	9.0	1650	795	1150	364	87.0	NA	55	3.30
	Average	7.5	652	299	115	56	23.5	NA	0.79	0.49
	StdDev	0.4	203	105	82	57	17.1	NA	2.75	0.51
	Count	403	400	401	395	76	252	NA	398	266
J.P. Nagar	Min	7.0	200	160	12	10	1.2	NA	0.25	0.10
	Max	8.5	868	612	475	96	65.0	NA	4.00	6.04
	Average	7.6	314	329	273	46	8.9	NA	0.48	0.72
	StdDev	0.3	95	65	90	33	9.6	NA	0.23	0.28
	Count	515	509	511	515	18	241	NA	513	231
Moradabad	Min	6.9	170	160	28	19	1.0	NA	0.15	0.01
	Max	8.2	507	322	140	252	10.0	NA	85	1.60
	Average	7.7	300	238	69	40	2.3	NA	0.88	0.12
	StdDev	0.2	55	32	18	19	1.6	NA	3.61	0.07
	Count	1038	1037	1034	1036	673	367	NA	1038	1039
Pilibhit	Min	6.5	144	100	24	156	1.0	0.01	0.02	0.03
	Max	8.5	600	1050	1050	200	445	0.50	14	14.5
	Average	7.7	244	267	223	178	30.6	0.09	0.5	0.7
	StdDev	0.5	68	206	308	31	31.0	0.09	1.0	1.3
	Count	1682	1144	1800	1813	2	641	148	1707	1816
Rampur	Min	6.9	202	198	45	15	NA	NA	0.20	NA
	Max	8.4	382	337	76	49	NA	NA	0.36	NA
	Average	7.6	281	261	64	29	NA	NA	0.27	NA
	StdDev	0.4	59	34	9	9	NA	NA	0.05	NA
	Count	22	22	22	20	22	NA	NA	22	NA

Table 1 continued

District name	Stat	pH	TDS	TH	Cl	SO_4	NO_3	As	F	Fe
Shahjahanpur	Min	6.5	120	NA	10	NA	0.5	NA	0.01	0.01
	Max	9	1000	NA	642	NA	232	NA	15.3	14
	Average	6.9	445	NA	149	NA	14.0	NA	0.44	0.40
	StdDev	0.4	101	NA	80	NA	20.9	NA	0.42	0.41
	Count	7500	10,815	NA	10,852	NA	9976	NA	10,745	10,324
Uttarakhand state										
Almora	Min	6.4	NA	NA	NA	0.1	0.01	NA	0.01	0.01
	Max	8.3	NA	NA	NA	36	20	NA	1.6	5.84
	Average	7.3	NA	NA	NA	3.4	0.34	NA	0.08	0.16
	StdDev	0.3	NA	NA	NA	3.5	1.22	NA	0.16	0.68
	Count	1067	NA	NA	NA	721	771	NA	572	303
Chamoli	Min	6.5	NA	26	NA	0.06	0.03	NA	0.01	0.01
	Max	8.5	NA	194	NA	26	16	NA	2.44	0.8
	Average	7.5	NA	65	NA	2.5	0.46	NA	0.17	0.13
	StdDev	0.3	NA	24	NA	3.4	0.66	NA	0.22	0.07
	Count	1389	NA	1352	NA	927	1373	NA	1361	1082
Garhwal	Min	6.2	NA	25	6	0.1	0.08	0.01	0.01	0.01
	Max	8.3	NA	350	120	130	23	0.01	1.5	5
	Average	7.5	NA	105	10	6.24	1.48	0.01	0.22	0.11
	StdDev	0.2	NA	75	10	12.49	1.88	0.01	0.17	0.22
	Count	*699*	*NA*	*605*	*459*	*586*	*683*	*138*	*426*	*570*
Nainital	Min	6.5	NA	26	6	0.6	0.05	NA	0.01	0.01
	Max	8.8	NA	578	71	124	30.8	NA	1.81	2.5
	Average	7.6	NA	150	15	16.2	2.3	NA	0.28	0.11
	StdDev	0.4	NA	110	8	28.2	12.4	NA	0.21	0.19
	Count	*639*	*NA*	*638*	*617*	*505*	*636*	*NA*	*623*	*424*
U.S. Nagar	Min	6.2	NA	37	NA	1	0.15	NA	0.09	NA
	Max	7.9	NA	536	NA	98	4.16	NA	1.37	NA
	Average	6.9	NA	97	NA	30.7	1.6	NA	0.59	NA
	StdDev	0.3	NA	42	NA	25.2	0.7	NA	0.24	NA
	Count	403	NA	401	NA	403	403	NA	402	NA
Total	Min	6.2	100	25	6	0.06	0.01	0.01	0.01	0.01
	Max	9.0	2000	1050	1150	600	886	0.5	85	14.5
	Average	7.4	494	251	163	105	15	0.1	0.5	0.4
	StdDev	0.6	219	124	160	112	20	0.1	1.1	0.5
	Count	23,216	21,942	15,761	24,610	12,018	24,105	318	26,818	24,773

Unit—mg/l except pH

NA not analyzed

generally not advisable for industrial sector. Pathak et al. (2008) also reported that TDS is high in most of the groundwater samples collected from the Moradabad city and exceeds the limit (>500 mg/l) set by WHO (2011) and BIS (2012).

In the RSB, chloride in groundwater varies from 6 to 1150 mg/l with an average value of 163 ± 160 mg/l (Mean $\pm$ SD) ($n = 24{,}610$). Maximum chloride concentrations in Bareilly, Hardoi, Pilibhit, Badaun and Shahjahanpur districts exceed 1000 and 500 mg/l (Table 1). In Pilibhit district, 17 % of groundwater samples exceed the $Cl > 500$ mg/l (Table 2). Generally, very low TDS and chloride in groundwater are recorded in the upstream districts, while high TDS is reported in the downstream districts (Fig. 2; Tables 1, 2). Chakraborti et al. (2011) reported that groundwater in the riparian states of Bihar, Haryana, Rajasthan and Uttar Pradesh of the Ganges River Basin has high salinity due to excessive

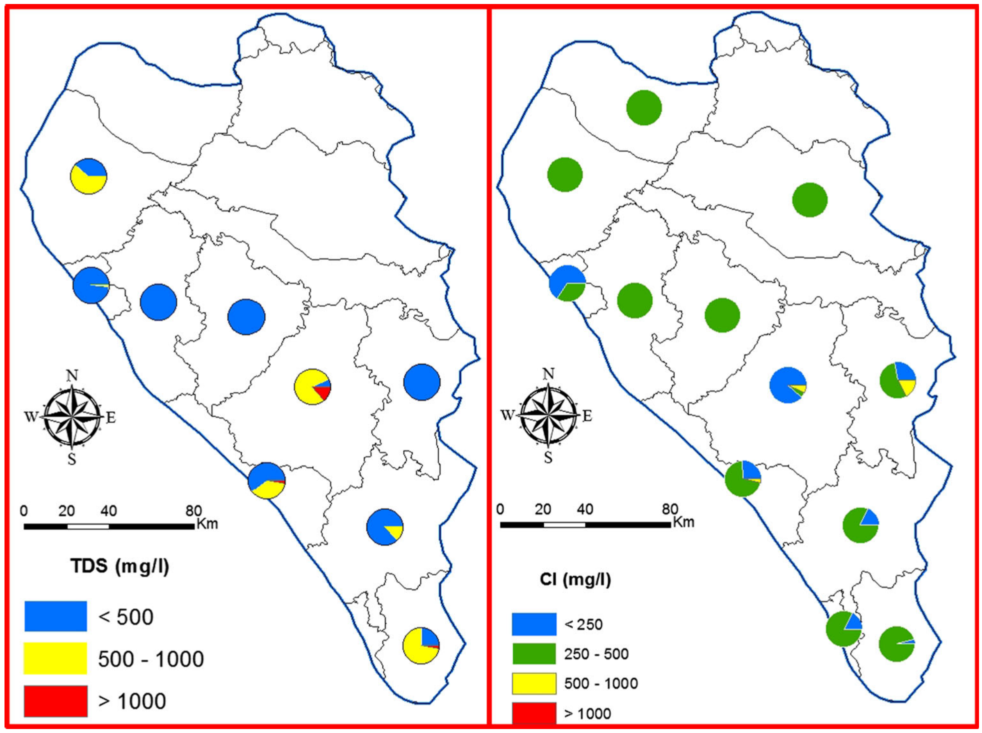

Fig. 2 Distribution of total dissolved solids (TDS) and chloride (Cl) in groundwater in RSB districts

usage of groundwater for irrigation. According to the CGWB (2009), groundwater in Bareilly, U.S. Nagar and Chamoil districts in the RSB is highly saline (Table 3). Further, they reported that water samples collected from springs are less saline compared to hand pumps and dug wells (Table 3). Nandimandalam (2012) also reported that

Table 2 Number of samples exceeding the BIS and WHO standards and its percentage for selected physicochemical parameters in groundwater, RSB Districts

District name	TDS > 500	TH > 600	Cl > 250	Cl > 500	SO_4 > 200	NO_3 > 45	As > 0.05	F > 1.5	Fe > 0.3	Fe > 1
Uttar Pradesh state										
Bareilly	2416 (93)	0	2271 (88)	186 (7)	1301 (51)	2 (0.1)	2 (6)	0	1394 (55)	0
Bijnor	2151 (61)	0	3 (0.1)	0	3	2 (0.1)	NA	4 (0.1)	1740 (49)	105 (3)
Budaun	756 (40)	0	556 (25)	71 (3)	1803 (83)	1 (0.01)	NA	5 (0.2)	31(2)	1 (0.1)
Farrukhabad	NA	0	130 (17)	0	NA	0	NA	0	4 (1)	2 (0.3)
Hardoi	301 (75)	2 (0.5)	15 (4)	1	1	24 (10)	NA	2 (0.5)	127 (48)	28 (11)
J.P. Nagar	8 (2)	2 (0.4)	335 (65)	0	0	6 (2)	NA	2 (0.4)	32 (14)	10 (4)
Moradabad	1 (0.1)	0	0	0	3	0	NA	3 (0.3)	2 (0.2)	1 (0.1)
Pilibhit	2 (0.2)	121 (7)	503 (28)	311 (17)	0	112 (18)	76 (51)	76 (4)	961 (53)	89 (5)
Rampur	0	0	0	0	0	NA	NA	0	NA	NA
Shahjahanpur	1465 (14)	NA	1966 (18)	1	NA	1554 (16)	NA	67 (0.6)	4346 (42)	342 (3)
Uttarakhand state										
Almora	NA	NA	NA	NA	0	0	NA	2 (0.3)	24 (8)	6 (2)
Chamoli	NA	0	NA	NA	0	0	NA	6 (0.4)	6 (1)	0
Garhwal	NA	0	0	0	0	0	0	0	1 (0.2)	1 (0.2)
Nainital	NA	0	0	0	0	0	NA	1	25 (6)	3 (0.7)
U.S. Nagar	NA	0	NA	NA	0	0	NA	0	NA	NA
Total	7100 (32)	125 (0.8)	5779 (24)	565 (2)	3111 (26)	1702(7)	78 (24)	168 (0.8)	8693 (35)	588 (2)

Unit—mg/l

NA not available

Table 3 Range of physicochemical parameters in groundwater in selected districts, RSB (Compiled from CGWB 2009)

Parameters	Chamoli		Nainital		U.S. Nagar	Bareilly	Moradabad	Rampur
	HP	Springs	HP	Springs	DW/HP	DW/HP	DW/HP	DW/HP
EC	83–1080	62–680	275–500	175–467	262–1300	350–1610	300–1080	232–900
pH	7.80–8.20	7.80–8.20	8.10–8.20	8.10–8.20	7.8–8.3	NA	NA	NA
Calcium	8–44	4–40	8–64	16–32	8–40	NA	NA	NA
Magnesium	2.4–66	2.4–72	15–43	12–44	10–58	NA	NA	NA
Sodium	1.5–106	0.5–19	6.4–34	3.5–21	1.4–46	NA	NA	NA
Potassium	1–39	0.4–9.5	1.1–4.5	0.9–3.8	0.4–68	NA	NA	NA
Bicarbonate	37–293	18–360	146–268	98–195	18–262	NA	NA	NA
Chloride	3.5–135	3.5–35	7.1–21	7.1–21	7–270	NA	NA	NA
Nitrate	BDL-130	BDL-24	BDL-17	BDL-8.8	0.5–63	BDL-205	NA	1.7–48
Fluoride	NA	BDL-0.89	BDL-0.17	BDL- 0.30	0.1–0.4	NA	NA	0.11–0.20
TH as $CaCO_3$	35–305	35–350	150–260	100–240	120 –300	NA	NA	250–280
Arsenic	NA	NA	NA	NA	NA	0.001–0.034	BDL-0.070	NA
Copper	NA	NA	NA	NA	0.02–0.03	NA	NA	NA
Lead	NA	NA	NA	NA	0.01–0.03	NA	NA	NA
Zinc	NA	NA	NA	NA	0.03–1.09	NA	NA	NA
Iron	NA	NA	NA	NA	0.12–3.00	NA	NA	NA
Chromium	NA	NA	NA	NA	0.02–0.13	NA	NA	NA
Manganese	NA	NA	NA	NA	0.10–3.20	NA	NA	NA
Total samples	53	31	NA	NA	63	NA	NA	NA

Unit—mg/l except EC (μS/cm) and pH

NA not available, *BDL* below detection limit, *DW* dug wells, *HP* hand pumps

groundwater in the shallow aquifer in Varanasi city is more mineralized (TDS 629 mg/l, average) than the deep aquifers (TDS 423 mg/l, average).

Total hardness

Hardness is a common but an important parameter that to assess the suitability of groundwater for drinking, domestic and industrial purposes (Karanth 1987). Hard water produces unpleasant taste, reduces the ability of soap to form lather and increases scale formation in pipes and on plumbing fixtures. In the RSB, the groundwater total hardness (TH) (in the form of $CaCO_3$) varies from 25 to 1050 mg/l with an average of 251 $\pm$ 124 mg/l (mean $\pm$ SD) ($n = 15{,}761$) (Table 1). According to the WHO (2011) and BIS (2012), the desirable and permissible limits are 100–500 mg/l and 300–600 mg/l, respectively. In the RSB, TH is more than 300 mg/l in 28 % of groundwater samples, which are collected mostly from downstream districts (i.e., Bareilly > Budaun > Bijnor > Pilibhit > J.P.Nagar > Hardoi) (Fig. 3). Likewise, the average groundwater TH exceeds 300 mg/l in Bareilly, Budaun and J.P. Nagar districts (Table 1). However, TH is $\leq$600 mg/l in 99 % samples in the study region (Fig. 3; Tables 1, 2).

Groundwater quality is again classified using TH as soft (TH < 75 mg/l), moderately hard (75–150 mg/l), hard (150–300 mg/l) and very hard (>300 mg/l) (US EPA 1986). Based on this classification, the groundwater samples in the RSB can be classified into soft (9.7 %), moderately hard (14.8 %), hard (47.5 %) and very hard (28 %) classes. Pathak et al. (2008) reported that groundwater hardness in Moradabad city varies from 136 to 836 mg/l and 48 % of samples show TH > 300 mg/l. In the upstream districts, the average TH is less than or equal to 150 mg/l (Table 1; Fig. 3).

Nitrate and sulfate

In the RSB, groundwater in most of the districts is affected by nitrate contamination, especially in the downstream districts (Table 1). Nitrate is a relatively stable compound and has high mobility compared to other nitrogen species. Excess nitrate levels (NO_3 > 45 mg/l) in drinking water cause serious health issues such as methemoglobinemia or blue baby syndrome, a condition found especially in the infants under 6 months (WHO 2009). Prolonged ingestion of high nitrate in human beings is linked to gastric problems due to the formation of nitrosamines, which are carcinogenic.

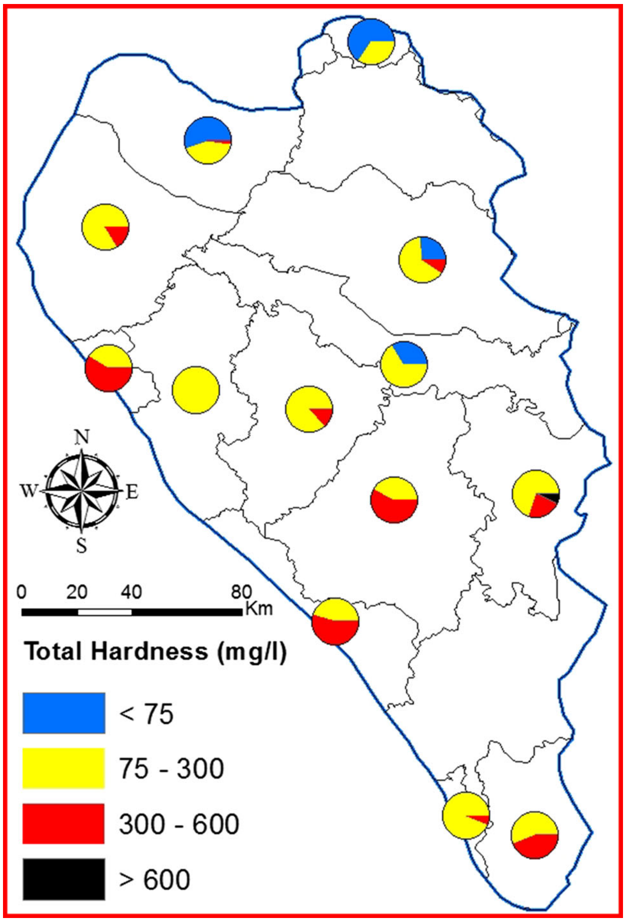

Fig. 3 Distribution of total hardness (TH) in groundwater in RSB districts

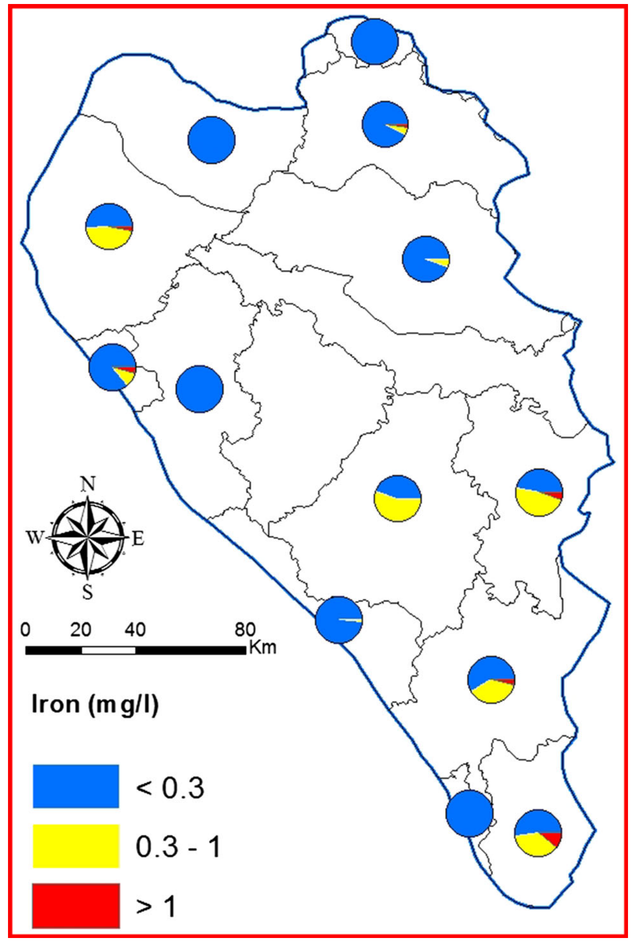

Fig. 4 Iron distribution in groundwater in RSB districts

In the RSB, the groundwater nitrate varies from <1 to 886 mg/l with an average value of 15 ± 20 mg/l (Mean ± SD) ($n = 24{,}105$). The maximum nitrate concentrations recorded are very high in some districts such as Bijnor, Pilibhit, Budaun, Shahjahanpur, Hardoi, Bareilly and J.P. Nagar (Table 1). The percentage of samples that exceed the WHO (2011) and BIS (2012) standards are high in Pilibhit (18 %) and Shahjahanpur districts (16 %) followed by Hardoi district (10 %) (Table 2). CGWB (2009) also reported the groundwater nitrate concentrations in the selected districts in the RSB (Table 3). In the spring water, the nitrate concentration is less than 25 mg/l. It is understandable that spring water originates from the deep confined aquifer, which is generally free from contamination. Nevertheless, the nitrate content is high in the shallow tube wells and dug wells. Nandimandalam (2012) also reported that nitrate content in the shallow aquifer is three times higher than in deep aquifer in Varanasi city. According to CGWB (2009), 33 % of groundwater samples collected from Moradabad district show $NO_3 > 45$ mg/l. Likewise, CGWB (2009) observed high nitrate levels in Bareilly district, especially Bhojipura region, and concluded that excess fertilizer applications and waste disposal are the major sources for nitrate in groundwater. Similar results are also reported in lower Varuna River basin and lower Kali watershed Uttar Pradesh (Raju et al. 2009; Khan et al. 2015).

Sulfate is one of the least toxic anions, even though the dehydration is observed at high concentrations. As per the WHO and BIS standards, the desirable and maximum permissible limit of sulfate in groundwater is 200 and 400 mg/l, respectively. Excess sulfate (>400 mg/l) causes various health issues such as gastrointestinal irritation, laxative effects, cathartic effects, dehydration from diarrhea at higher level (US EPA 1999a, b; WHO 2004). In the RSB, groundwater sulfate varies from <1 to 600 mg/l with an average of 105 ± 112 mg/l (Mean ± SD) ($n = 12{,}018$) (Table 1). Sulfate levels are less than 200 mg/l in 74 % of the groundwater samples in the study region. High groundwater sulfate content (>200 mg/l) is recorded in Badaun and Bareilly districts (Table 2).

Iron

In the RSB, high iron is reported in groundwater from most of the districts (Tables 1, 2; Fig. 4). For drinking water, the WHO (2011) and BIS (2012) recommended iron levels are $\leq$0.3 and $\leq$1 mg/l, respectively. Excess iron causes unpleasant metallic taste and rusty color in drinking water and stains in textiles. Iron deficiency symptoms are anemia, fatigue, immune system damage, and effects of children mental development and concentration disorder. Likewise, excess iron or iron overload causes gene mutation, haemochromatosis, fatigue, weight loss, joint pain, heart disease, liver problems and diabetes (WHO 2003). Excess iron damages the water equipment, corrosion followed by blockage in the water distribution pipes, etc.

In the RSB, the groundwater iron content varies from 0.01 to 14.5 mg/l with an average of 0.4 $\pm$ 0.5 mg/l (Mean $\pm$ SD) ($n = 24{,}773$). The maximum iron concentrations in groundwater are generally high in Bijnor, Budaun, J.P.Nagar, Pilibhit, Shahjahanpur, Almora and Garhwal districts (Table 1). Also, extreme groundwater iron concentrations (Fe $\geq$ 14 mg/l) are encountered in Pilibhit and Shahjahanpur districts (Table 1). Table 2 indicates that the iron content in almost 50 % of groundwater samples in Bareilly, Bijnor, Hardoi, Pilibhit and Shahjahanpur districts exceeds WHO drinking water standards (Fe > 0.3 mg/l) and some of them even exceed BIS standards (Fe > 1 mg/l). Other researchers also studied and reported high iron content in groundwater in the RSB. CGWB (2009) reported that the groundwater iron concentrations in U.S. Nagar range from 0.12 to 3 mg/l (Table 3). Kumar and Sinha (2008) also reported high iron concentration (Range 0.8–2.15 mg/l, Mean 1.47 mg/l) in groundwater in Moradabad city. Likewise, Rastogi and Sinha (2008) (Moradabad city, range 1.02–3.9 mg/l; average of 2.2 mg/l), Singh et al. (2009) (Bareilly district, range 0.09–0.92 mg/l; average 0.5 mg/l) and Sinha and Saxena (2006) (Hasanpur in J.P. Nagar district, range 0.09–0.92 mg/l; average 0.32 mg/l) studied the groundwater iron concentrations in the RSB.

Arsenic

Arsenic data are not available for all the districts in the RSB, and it is reported only for Bareilly, Pilibhit and Garhwal districts. Groundwater arsenic concentrations vary from 0.01 to 0.5 mg/l ($n = 318$) in the study region. The average arsenic concentrations in Bareilly and Pilibhit districts are 0.040 and 0.090 mg/l, respectively, and exceed the WHO (2011) recommended limit (Table 1). The Ministry of Drinking Water and Sanitation (MDWS) carried out a detailed survey to screen the groundwater arsenic in 51 districts in UP (MDWS 2011; Table 4). Table 4 indicates that Bareilly, Bijnor, Moradabad, Shahjahanpur and Pilibhit districts have higher arsenic content in groundwater and around 13 % of samples exceed the WHO (2011) recommended limit (As > 0.010 mg/l). In this list, arsenic contents in some groundwater samples are more than 0.050 mg/l (BIS recommendation). CGWB (2009) tested the groundwater arsenic content in Bareilly and Moradabad districts and their findings indicate the concentration ranges from 0.001 to 0.034 mg/l and BDL to 0.070 mg/l, respectively, in these districts (Table 3). Further, they documented that high arsenic (As > 70 µg/l) in groundwater is recorded in Ashiyana block, Moradabad district. Agarwal (2014) reported that Jal Nigam carried out a detailed survey for groundwater arsenic in Bareilly district. They found high levels of arsenic in groundwater in 19 villages, namely nine villages from Majhgavan block, five in Alampur Jafarabad block, three from Meerganj block and two in Fatehganj (west). According to Agarwal (2014), the worst affected village is Bahrauli.

Table 4 Groundwater arsenic content in UP districts, RSB (compiled from MDWS 2011)

District	No. of blocks	HP tested	No. of samples and %	
			10–50	>50
Bareilly	9	1571	238 (15)	22 (1)
Bijnor	7	1917	255 (13)	3 (0.2)
Budaun	11	1890	2	0
Farrukhabad	5	1726	0	0
Hardoi	10	3273	0	0
J P Nagar	4	760	0	0
Moradabad	4	654	95 (15)	8 (1)
Pilibhit	7	1647	55 (3)	0
Rampur	4	1112	0	0
Shahjahanpur	9	1193	159 (13)	3 (0.3)
Total	70	15,743	804 (5)	36 (0.2)

Unit—µg/l

HP hand pumps

Fluoride

In the RSB, fluoride contamination in groundwater is reported widely (Fig. 5; Tables 1, 2). Fluoride has significant mitigating effect against dental caries, and its presence in drinking water is beneficial if F $\leq$ 1 mg/l. However, the groundwater with high fluoride content (F > 1.5 mg/l) is not advisable for drinking as it causes serious health issues such as dental fluorosis, skeletal fluorosis (WHO 2011; BIS 2012). Mottling of teeth may occur if the groundwater fluoride exceeds 1.5 mg/l. Likewise, consumption of groundwater with high fluoride (3–6 mg/l) causes skeletal

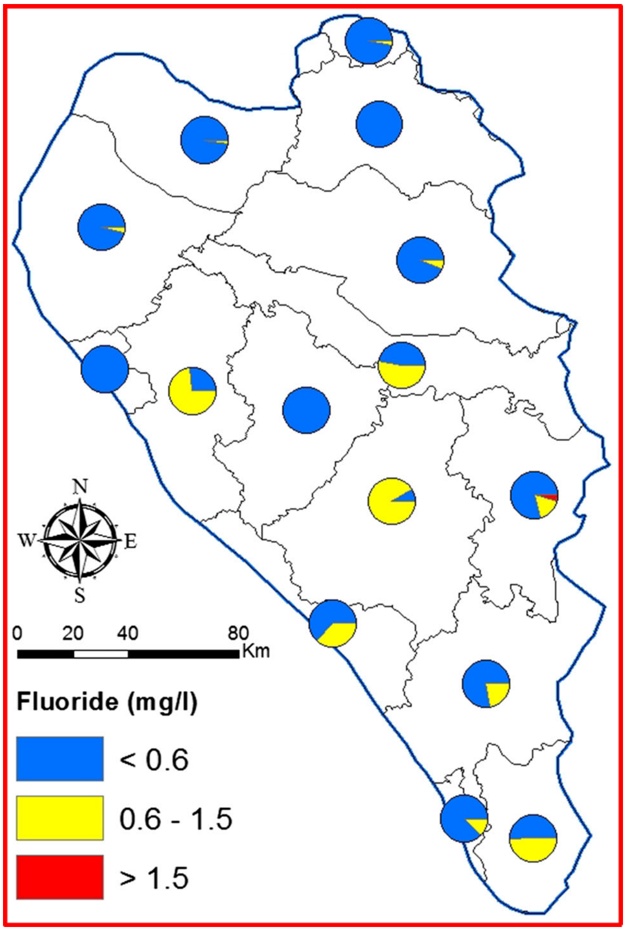

Fig. 5 Groundwater fluoride distribution in RSB districts

fluorosis. Also, continuous usage of groundwater with 10 mg/l of fluoride can result in crippling fluorosis.

In the RSB, the maximum fluoride concentrations in groundwater exceed 1.5 mg/l in most of the districts (Table 1; Fig. 5). In Pilibhit and Shahjahanpur districts, high fluoride (>1.5 mg/l) is documented in more samples (Table 2). However, only 168 (0.8 %) samples exceed the F > 1.5 mg/l in the total groundwater samples ($n = 26{,}818$) analyzed in this basin. CGWB (2009) also tested the groundwater samples in Chamoli, Nainital, U.S. Nagar and Rampur districts and reported that the groundwater fluoride concentrations are mostly less than 1 mg/l in these districts (Table 3). Kumar and Yadav (2011) also carried out a groundwater quality assessment in Shahzad Nagar block, Rampur district. They reported that the groundwater fluoride concentration varied from 0.76 to 2.2 mg/l with an average of 1.06 mg/l and few wells exceeded WHO (2011) limit (F > 1.5 mg/l). According to CWC/NRSC (2014), groundwater in almost of all parts of the Ganges basin is affected by fluoride contamination, especially Bihar, Chhattisgarh, Delhi, Haryana, Jharkhand, Madhya Pradesh, Rajasthan, Uttar Pradesh and West Bengal states. Singh et al. (2009) reported that groundwater fluoride concentrations in the selected sites in Bareilly district ranged from 0.31 to 1.9 mg/l with a mean value of 1.11 mg/l. Similarly, Sinha and Saxena (2006) also studied the groundwater quality in Hasanpur, J.P. Nagar district, and noted that groundwater fluoride varied from 0.31 to 1.57 mg/l with an average of 0.81 mg/l.

Table 5 Pearson correlation matrix for selected parameters in groundwater, RSB

	pH	TDS	TH	Cl	SO_4	NO_3
pH	1	−.098	−.106	−.310	−.340	−.171
P		*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
TDS	−.098	1	**0.521**	**0.648**	0.293	**0.526**
P	*0.000*		***0.000***	***0.000***	*0.000*	***0.000***
TH	−.106	**0.521**	1	**0.605**	**0.602**	0.492
P	*0.000*	***0.000***		***0.000***	***0.000***	*0.000*
Cl	−.310	**0.648**	**0.605**	1	**0.696**	**0.680**
P	*0.000*	***0.000***	***0.000***		***0.000***	***0.000***
SO_4	−.340	0.293	**0.602**	**0.696**	1	**0.670**
P	*0.000*	*0.000*	***0.000***	***0.000***		***0.000***
NO_3	−.171	**0.526**	0.492	**0.680**	**0.670**	1
P	*0.000*	***0.000***	*0.000*	***0.000***	***0.000***	

Bold and bold italic values indicate significant correlation

Italic values indicate $p \leq 0.01$

Other water quality studies in the RSB

Few site specific studies evaluated the metals and major ions in groundwater of this basin. Rastogi and Sinha (2008) studied the metal concentrations in groundwater in important public service places in Moradabad city and concluded that trace metals such as chromium, cobalt, nickel and copper were below detection limits, whereas lead and chromium were detected in trace amounts in the groundwater. Further, they noted that manganese concentrations varied from 0.206 to 0.266 mg/l with an average of 0.231 mg/l and exceeded the WHO (2011) drinking water standards (Mn ≤ 0.1 mg/l). Singh et al. (2009) evaluated the groundwater quality in the selected sites in Bareilly district and stated that the groundwater zinc concentration is between 0.2 and 2.20 mg/l with a mean value of 1.20 mg/l and that zinc expressed a positive correlation with iron. This observation implies that reducing environment enhances metals in this aquifer through the dissolution of metal oxides. Sinha and Saxena (2006) examined the groundwater quality in Hasanpur, J.P. Nagar district, and analyzed various parameters. In this study, the data show that groundwater from shallow domestic hand pumps (HPs) have high EC (>1000 µS/cm), TDS (>900 mg/l), TH (>500 mg/l), Ca (>120 mg/l), Mg (>40 mg/l), free CO_2

(>43 mg/l), Cl (>135 mg/l) and F (>1 mg/l) and less DO (<3 mg/l) compared to deeper HPs. In the case of iron and zinc, there is no significant variation between shallow and deeper wells in this study.

Source of contaminants

In the RSB, a detailed analysis and discussion about the process and mechanisms regulating groundwater chemistry and the sources of contaminants in groundwater are not possible due to lack of data. However, a correlation analysis was carried out using the available data (NRDWP 2014) (Table 5). Inter-elemental correlation analysis provides the information about the origin and source of variables and its evaluation pathway. Variables such as pH, As, Fe and F are not significantly correlated with other variables. TDS has a significant positive correlation ($p < 0.01$) with TH ($r^2 > 0.52$), Cl ($r^2 > 0.65$) and NO_3 ($r^2 > 0.53$) (Table 5). Besides this, Cl shows significant positive correlation with SO_4 ($r^2 > 0.7$) and NO_3 ($r^2 > 0.68$). Likewise, SO_4 exhibits strong positive correlation with NO_3 ($r^2 > 0.67$). All these variables are strongly interrelated and are originated mostly from same sources or process.

In the RSB, TDS, Cl, NO_3 and SO_4 are originated mostly from surface contamination sources. Groundwater salinity is directly linked to soil salinity and both are caused by evaporation, dissolution of evaporates, waterlogging, groundwater level rise, excessive usage of water in irrigation practices, industrial wastewater discharge, dumping sites, etc. (Jaglan and Qureshi 1996; Meena 2001; Raju et al. 2009; Misra 2011; Nandimandalam 2012; Khan et al. 2015).

In the RSB, surface contamination sources are a major cause of high salinity, chloride, nitrate and sulfate in groundwater. This observation is well supported by correlation analysis (Table 5). In the study region, domestic sewage and animal waste are the major source of nitrate in groundwater along with agricultural practice (Chakraborti et al. 2011; Somasundaran et al. 1993). Field visits in the RSB found that accumulation of animal waste in huge heaps in the villages are very common. Poor sanitation facilities in villages and leakage from septic tanks enhance nitrate contamination in groundwater. Kamal et al. (2014) studied groundwater quality in J.P. Nagar district and concluded that nitrate, sulfate and phosphate in groundwater are mainly originated from anthropogenic sources based on groundwater quality assessment and XRD analysis of soil samples. Sinha and Saxena (2006) estimated low dissolved oxygen and high free CO_2 in the shallow aquifer, which indicates the infiltration of domestic wastewater, drainage/sewage lines and other surface contamination sources due to poor sanitation in this region. Other studies in the nearby region also reported similar observations (Raju et al. 2009; Nandimandalam 2012; Khan et al. 2015). Tyagi et al. (2009) also reported that chemical fertilizers and sugar factories wastewater induce the chloride and sulfate contamination in groundwater in Muzaffarnagar district, Uttar Pradesh.

In contrast to this, iron is generally originated by natural process and controlled by physicochemical and microbiological factors such as natural weathering, oxidation/reduction, adsorption/desorption, pH, organic matter, soil texture (Rajmohan et al. 2014 and references therein). Under reducing conditions, dissolution of ferric oxides or oxyhydroxides such as hematite (Fe_2O_3), goethite (FeOOH) in the soil will enhance iron concentration in groundwater. In the RSB, reductive dissolution of iron oxides seems to be major controlling factor for high iron concentrations in groundwater. In this region, thick clay layers is observed, which forms semi-confined/confined aquifer in this region. In the RSB, Singh et al. (2009) and Sinha and Saxena (2006) reported that groundwater iron has strong positive correlation with manganese and zinc, which justifies that all are originated by the reduction processes.

Like iron, arsenic mostly originated from geogenic sources in the Ganges basin (Rajmohan and Prathapar 2014 and references therein). Pandey et al. (2009) reported the arsenic concentrations in various water sources (hand pumps, tube wells, dug wells) in Ballia district, Uttar Pradesh, and concluded that various geogenic processes are responsible for high arsenic in groundwater. MDWS (2011) also confirmed the geogenic sources, especially young alluvial deposits for high groundwater arsenic in Ballia district. Hence, arsenic contamination in groundwater in the RSB is mainly due to geological formations (younger alluvium) and a detailed discussion about the processes is reported in Rajmohan and Prathapar (2014).

In the case of fluoride, groundwater collected from shallow domestic hand pumps (HP) in Hasanpur, J.P. Nagar district, shows high fluoride (>1 mg/l) compared to deeper HPs (government installed HP) (Sinha and Saxena 2006). Further, fluoride has a strong correlation with chloride in the shallow wells. This observation implies that infiltrating sewage water can be increased the dissolution of fluoride minerals in the unsaturated zone or fluoride may be originated from surface contamination sources along with natural sources such as infiltration of evaporated water (irrigation return flow and surface runoff water) (Datta et al. 1996; Misra and Mishra 2007). The usage of phosphatic fertilizers in agricultural practice and clays in ceramic industries also enrich the high fluoride in groundwater (Datta et al. 1996; Kundu and Mandal 2009).

Groundwater quality issues in Ramganga Sub-Basin

Figure 6 illustrates the overall district-wise groundwater quality issues in the study region. This map explains the

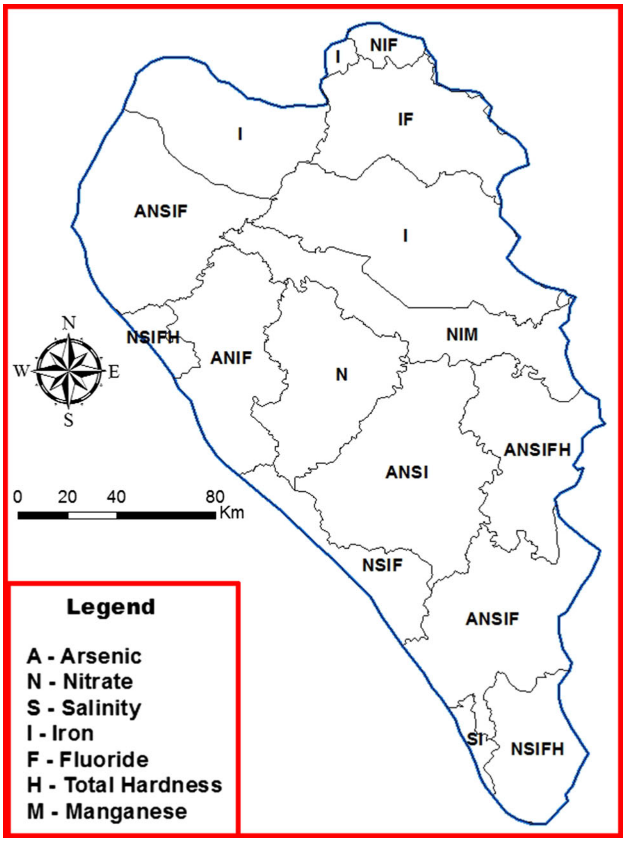

Fig. 6 Groundwater quality issues in the RSB districts. *Index* indicates that groundwater contamination is identified by specific parameter in this district (i.e., N—nitrate contamination ($NO_3 > 45$ mg/l) is identified in this district). (Compiled from NRDWP 2014; MDWS 2011; CGWB 2009, 2014a)

contaminants identified in the groundwater and shows which concentrations exceed the drinking water standards in each district. Figure 6 shows that groundwater quality is largely deteriorated in Pilibhit, Shahjahanpur, J.P.Nagar, Bijnor, Moradabad, Hardoi and Bareilly districts in the study region. Besides, nitrate and iron contaminations are encountered in groundwater from most of the districts.

Conclusions and recommendations

In the RSB, groundwater in most riparian districts are affected by nitrate, iron, salinity and fluoride, and their concentrations exceed the standards prescribed for drinking water by the Bureau of Indian Standards (BIS 2012) and World Health Organization (WHO 2011). The shallow aquifers have higher concentrations of most of the ions due mainly to the infiltration of wastewater and contaminated surface water. Poor sanitation, improper disposal of domestic sewage water and manures, and irrigation return flows are major sources of groundwater contamination.

This study recommends the following options for groundwater development and management in the RSB.

- Conduct further ground level studies to identify the contamination sources, especially in poor water quality regions. The available databases in the public domain are not adequate.
- Avoid the vertical leakage during the installation of hand pumps and tube wells. (Wastewater accumulated near the hand pumps and contaminated groundwater from shallow unconfined aquifer affect groundwater quality).
- Proper disposal or reuse of animal waste (i.e., cow dung) to reduce the accumulation and surface water contamination.
- Promote groundwater recharge methods such as rainwater harvesting and Managed Aquifer Recharge (MAR) to reduce solute load in groundwater by dilution and improve the quality.
- Conduct awareness program about water-borne diseases, and importance of water quality and waste management to protect groundwater.
- Proper use of agrochemicals in various agroecological regions.

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Compliance with ethical standards

Conflict of interest The authors declare no conflict of interests.

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