

Major ion chemistry of the Son River, India: Weathering processes, dissolved fluxes and water quality assessment

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River Son, draining diverse lithologies in the subtropical climate of the peninsular sub-basin of the Ganga basin, is one of the major tributaries of the Ganga River. The chemistry of major ions in the surface water of the Son River was studied in detail to determine various source(s) and processes controlling its water chemistry, seasonal and spatial variations in water chemistry, dissolved fluxes and chemical denudation rate (CDR). The study shows that Ca^{2+} , Mg^{2+} and HCO_3^- are major ionic species in the river water. Most of the measured parameters exhibit a relatively lower concentration in the post-monsoon as compared to pre-monsoon season. The water chemistry highlights the influence of continental weathering aided by secondary contributions from ground water, saline/alkaline soils and anthropogenic activities in the catchment. Results also reflect the dominance of carbonate weathering over silicate weathering in controlling water composition. The Son River delivers about 4.2 million tons of dissolved loads annually to the Ganga River, which accounts for $\sim 6\%$ of the total annual load carried by the Ganga River to the Bay of Bengal. The average CDR of the Son River is $59.5 \text{ tons km}^{-2} \text{ yr}^{-1}$, which is less than the reported $72 \text{ tons km}^{-2} \text{ yr}^{-1}$ of the Ganga River and higher than the global average of $36 \text{ tons km}^{-2} \text{ yr}^{-1}$. The water chemistry for the pre-monsoon and post-monsoon periods shows a strong seasonal control on solute flux and CDR values. The water chemistry indicates that the Son River water is good to excellent in quality for irrigation and also suitable for drinking purposes.

1. Introduction

Rivers are major dynamic water bodies responsible for most of the continental input to the world ocean and geochemical cycling of elements among continent–river–ocean systems. Rivers around the globe deliver about 90% of the continental weathering products along with anthropogenic inputs in the form of dissolved and particulate load into the world oceans (Garrels *et al.* 1975). A

number of detailed geochemical studies are available on world rivers, dealing with the origin and fate of elements/pollutants, explaining various processes controlling river water chemistry on the basin scale. These studies also explain the exogenic cycling of elements in the continent–river–ocean systems (Livingstone 1963; Reeder *et al.* 1972; Carbonnel and Meybeck 1975; Subramanian 1979; Hu *et al.* 1982; Meybeck 1982, 2005; Stallard and Edmond 1983; Sarin *et al.* 1989; Bluth and

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Kump 1994; Zhang *et al.* 1995; Galy and France-Lanord 1999; Hren *et al.* 2007; Li *et al.* 2009). Indian rivers have also been studied to understand (i) hydrological and environmental characteristics of river basins, (ii) influence of basin geology, tectonics, climate and anthropogenic activities on riverine chemistry and (iii) elemental fluxes from rivers to oceans (Subramanian 1979, 1983; Biksham and Subramanian 1988; Sarin *et al.* 1989; Chakrapani and Subramanian 1990; Ramanathan *et al.* 1994; Krishnaswami and Singh 1998; Ahmad *et al.* 1998; Singh and Hasnain 1999; Dalai *et al.* 2002; Singh *et al.* 2005; Sharma and Subramanian 2008; Jha *et al.* 2009; Rengarajan *et al.* 2009; Gupta *et al.* 2011).

In order to understand the dynamics of large river systems properly, it is essential to study the medium and small rivers present within their basins. For example, the Ganga River system has several medium to small-sized tributaries, and the water chemistry of tributaries significantly influences the composition of the Ganga River water (Sarin *et al.* 1989). Previous studies on the Ganga River system were mainly confined to the Himalayan catchments and north joining tributaries, whereas peninsular rivers joining from the south have received little attention. The Son River, a major tributary in the peninsular sub-basin of the Ganga River, has been studied for water chemistry and quality assessment for only a few locations (Subramanian 1984; Sarin *et al.* 1989; Rai *et al.* 2010; Rani *et al.* 2011). Sarin *et al.* (1989) reported the significant silicate weathering rather than carbonate weathering for the Son basin, whereas Rai *et al.* (2010) reported higher carbonate weathering rate than silicate weathering

rate based on the water chemistry at Koelwar. No serious attempts have been made to study the weathering processes in the Son River on a basin scale. Therefore, in order to have better understanding, a detailed hydrogeochemical investigation of the Son River has been carried out to determine the major ion chemistry and their source(s), to understand the role of weathering and other geochemical processes (precipitation and dissolution of minerals/salts, redox processes, etc.) in controlling the water composition of the Son River in the peninsular sub-basin of the Ganga River. The geochemical data have also been used to assess the dissolved fluxes and chemical denudation rate of the Son River, its contribution to water chemistry of the Ganga River and suitability of its water for irrigation and drinking purposes.

2. Study area

The Son River basin is one of the major sub-basins of the Ganga River basin (figure 1). Unlike the Himalayan-glacial-fed tributaries of the Ganga River, the rain-fed Son River is the principal peninsular tributary of the river Ganga. The Son River originates in the Amarkantak hills of Maikal range at an elevation of 1030 m in central India and traverses for about 784 km, of which 500 km lies in the Madhya Pradesh, 82 km in Uttar Pradesh and remaining 202 km in Jharkhand and Bihar states of India. The total catchment area of the Son River is 71,259 km² (Rao 1975). After its origin, it flows north-northwest through Madhya Pradesh, then it turns sharply eastward and encounters the southwest-northeast running Kaimur group of the

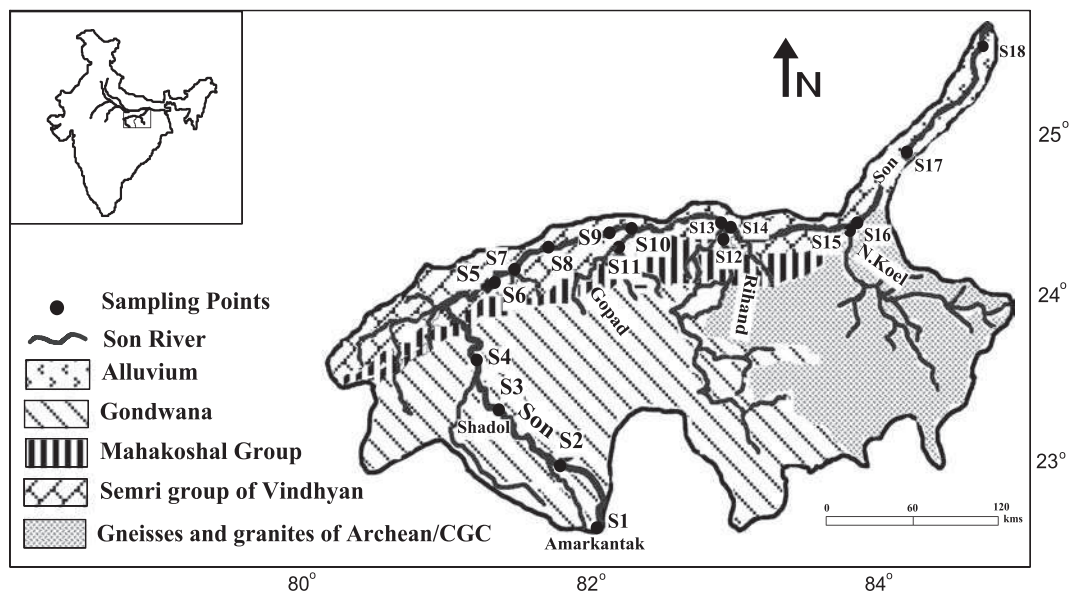


Figure 1. Geological map of Son River basin with sampling locations.

Vindhyan Super Group. Then it flows in the east–northeast direction, and parallels to the Kaimur range, through Uttar Pradesh, Jharkhand and Bihar states before joining the river Ganga near Patna city of Bihar.

From its origin to the mouth the Son River drains diverse lithological units of the peninsula. The major lithological units appear within the Son River basins are of the Gondwana and Vindhyan Super Groups, Mahakoshal Group, Chhotanagpur Granitic Complex and Quaternary Alluvium (figure 1). The Son River principally flows through sandstones and shales of the Gondwanas, sandstones, shales and carbonates of the Semri, sandstones, shale and minor carbonates of the Kaimur Groups of the Vindhyan Super Group, and the Quaternary Alluvium. Tributaries of the Son River, the Rihand, North Koel and Gopad, flow through the Gondwanas, Mahakoshal Group, Archean gneiss and Chhotanagpur Granitic Complex (Gneisses, granites) (Lakshmanan 1970; Ray *et al.* 2003; Ramakrishnan and Vaidyanadhan 2008). Major groups of soils of the Son basin are red yellow soil, red sandy soil and younger alluvial soil. The upper reaches of the Son River is forested while in lower reaches it consists of scrub and grasses. The Son basin experiences a subtropical climate having hot dry summer (March–June), monsoon rain (July–October) and winter (November–January) seasons.

3. Sample collection and analytical methodology

Thirty-five water samples at 18 locations (Supplementary data) on the Son River and its tributaries were collected during the pre-monsoon (May) and post-monsoon (November) seasons of the year 2010. Water samples collected from the mouth of the Son before meeting the Ganga at Koelwar during the pre-monsoon (April) and monsoon (August) seasons of the year 2013 were utilized for the estimation of flux and CDR. Water samples were collected in one litre narrow-mouth pre-washed polyethylene bottles from the main river channel, tributaries and reservoir (figure 1). One aliquot of the collected samples (100 ml) were filtered on site using Millipore syringe filters (0.45 μm) and acidified immediately by using supra pure HNO_3 and kept carefully till analysis. Another aliquot of the samples (500 ml) were filtered through 0.45 μm Millipore membrane filters to separate suspended sediments and preserved at 4°C for further analysis. Water samples were analysed for pH and electrical conductivity (EC) using pH-EC meter. Total dissolved solid (TDS) was calculated by summation of all dissolved components.

Major cations (Ca^{2+} , Mg^{2+} , Na^+ and K^+) in acidified samples and major anions (F^- , Cl^- , HCO_3^- , SO_4^{2-} – NO_3^-) and dissolved silica in nonacidified samples were analysed following standard analytical methods (APHA 1998). Concentration of bicarbonate was determined by acid titration method and F^- , Cl^- , SO_4^{2-} and NO_3^- were analysed on an ion chromatograph (Dionex Dx-120) using anion (AS12A/AG12) columns coupled to an anion self-regenerating suppressor (ASRS) in recycle mode. Concentration of Ca^{2+} and Mg^{2+} were determined using ICP-AES (Ultima-2, JY Horiba). Na^+ and K^+ were measured by AAS (Varian, 280 FS) in flame mode. Dissolved silica concentration in water was measured by molybdosilicate method with the help of UV–VIS spectrophotometer. The analytical precision was maintained by running a known standard after every 10 samples. An overall precision was obtained below 10% for all the samples.

4. Results and discussion

4.1 Major ion chemistry

The major ion chemistry of the Son River, its tributaries and reservoir water for pre-monsoon and post-monsoon seasons are given in table 1(a). The table also shows pH, EC, total hardness (TH), sodium adsorption ratio (SAR), %Na and residual sodium carbonate (RSC) values. Statistical analysis of the data shows that the total cations (TZ^+) and total anions (TZ^-) are coupled by the relation $\text{TZ}^+ = 0.908\text{TZ}^- \pm 32.4$ with a correlation coefficient $r^2 = 0.95$ for the analysed water samples. Like other Indian rivers, water samples in the Son River and its tributaries are alkaline in nature (Subramanian 1979). The water found to be slightly acidic at the origin (S-1), which may be due to high organic loading in the forested region. The measured average pH of the river water is slightly higher in the pre-monsoon (8.0) as compared to the post-monsoon season (7.5). The electrical conductivity (EC) varies between 83–1314 $\mu\text{S cm}^{-1}$ in pre-monsoon and 68–551 $\mu\text{S cm}^{-1}$ during post-monsoon seasons with average values of 292 $\mu\text{S cm}^{-1}$ and 252 $\mu\text{S cm}^{-1}$, respectively. The total dissolved solid (TDS) concentration varies between 78 and 797 mg l^{-1} (average 234 mg l^{-1}) during the pre-monsoon and between 64 and 412 mg l^{-1} (average 220 mg l^{-1}) in the post-monsoon season.

Major anions in the Son River surface water account for 69% of the TDS. Bicarbonate is the most dominant ion in the analysed water samples, accounting for 58% of the total dissolved load. The concentration of HCO_3^- varies from 688 to

Table 1(a). *Hydrogeochemical characteristics of surface water of the Son River.*

Sl. no.	Samp. location	pH	EC	TDS	F	Cl	HCO ₃	SO ₄	NO ₃	Silica	Ca	Mg	Na	K	TH	PCO ₂	SIC	SID	SAR	RSC	%Na
1a	Amarkantk	6.0	83	78	16	56	688	7	89	219	220	99	113	5	32	-1.34	-2.82	-5.57	0.20	0.06	15.7
1b		6.8	68	64	8	43	606	10	44	153	175	95	91	27	27	-2.19	-2.17	-4.20	0.17	0.07	17.8
2a	Annupur	8.0	276	218	31	141	2016	91	9	455	719	247	635	79	97	-2.88	0.16	0.26	0.65	0.09	27.0
2b		7.5	221	182	14	130	1704	127	4	262	666	247	405	90	91	-2.45	-0.45	-0.92	0.42	-0.13	21.3
3a	Diapiper	8.2	1314	797	25	6767	2950	820	8	372	3640	876	4167	312	452	-2.91	1.23	2.25	1.96	-6.08	33.1
3b		7.5	551	412	25	2279	2016	844	1	251	1312	498	1827	127	181	-2.38	-0.08	-0.17	1.36	-1.60	35.1
4a	Jaisingnagar	8.4	315	256	58	564	2065	260	8	498	699	436	544	64	114	-3.26	0.56	1.32	0.51	-0.20	21.1
4b		7.7	304	253	16	423	2344	157	1	340	856	411	539	80	127	-2.51	0.00	0.09	0.48	-0.20	19.7
5a	Bansagar	8.7	189	162	19	127	1655	60	3	219	581	247	270	44	83	-3.66	0.69	1.40	0.29	0.01	15.9
5b		7.5	174	161	28	124	1639	54	21	234	551	218	222	77	77	-2.47	-0.55	-1.09	0.25	0.09	16.1
6a	Khand	8.2	222	184	19	135	1868	58	3	259	674	247	348	62	92	-3.11	0.30	0.57	0.36	0.03	18.2
6b		7.5	185	170	14	119	1754	55	2	234	571	251	270	82	83	-2.43	-0.50	-0.94	0.30	0.11	17.6
7a	Rampurnaikin	8.3	221	190	32	423	1786	9	5	400	479	263	426	97	74	-3.23	0.23	0.62	0.49	0.31	26.0
7b		7.6	265	237	20	144	2589	42	14	261	761	399	452	68	116	-2.37	-0.11	-0.08	0.42	0.27	18.3
8a	Churhat	8.2	249	186	52	282	1688	30	10	476	417	259	561	110	68	-3.15	0.05	0.29	0.68	0.33	33.1
8b		7.8	222	196	14	105	2212	31	2	224	579	305	326	80	88	-2.64	-0.09	-0.06	0.35	0.44	18.7
9a	Dhehra	8.2	249	193	39	141	2016	2	13	339	332	399	709	100	73	-3.08	0.03	0.54	0.83	0.55	35.6
9b		7.7	239	214	15	102	2393	34	1	216	694	350	370	77	104	-2.50	-0.08	-0.05	0.36	0.31	17.6
10a	Khairpur	8.3	324	287	30	423	2901	43	5	485	841	465	583	69	131	-3.02	0.69	1.52	0.51	0.29	20.0
11a	Gopad River	7.9	151	134	29	155	1295	2	5	284	407	173	287	102	58	-2.97	-0.38	-0.72	0.38	0.14	25.1
11b		7.4	137	129	12	60	1377	19	5	193	409	185	187	82	60	-2.44	-0.85	-1.64	0.24	0.19	18.5
12a	Rihand River	7.5	143	120	57	141	967	104	8	266	347	152	387	59	50	-2.70	-0.98	-1.90	0.55	-0.03	30.9
12b		6.9	153	137	30	164	1246	95	34	183	374	173	431	82	55	-1.98	-1.43	-2.79	0.58	0.16	31.9
13a	Kargara	8.4	278	275	21	843	2622	49	5	410	789	387	457	87	118	-3.16	0.72	1.53	0.42	0.27	18.8
13b		7.6	259	234	15	89	2655	31	4	222	791	370	344	77	116	-2.36	-0.08	-0.08	0.32	0.34	15.4
14a	Chopan	7.9	225	200	48	702	1737	93	6	282	551	272	452	74	82	-2.84	-0.12	-0.14	0.50	0.09	24.2
14b		7.5	240	205	25	148	2212	76	6	219	616	280	400	78	90	-2.34	-0.37	-0.67	0.42	0.41	21.1
15a	Koel River	8.4	302	277	65	561	2786	69	6	317	791	321	740	79	111	-3.13	0.74	1.50	0.70	0.56	26.9
15b		7.9	385	365	28	235	3737	79	160	433	1080	518	1087	87	160	-2.51	0.51	1.10	0.86	0.55	26.8
16a	Japla	7.9	247	230	6	559	2131	78	5	400	684	309	465	77	99	-2.75	0.06	0.18	0.47	0.14	21.4
16b		7.6	258	229	19	161	2458	49	4	266	711	325	552	78	104	-2.39	-0.16	-0.25	0.54	0.39	23.4
17a	DOS	8.0	246	220	39	561	2016	82	8	365	634	300	465	74	93	-2.88	0.11	0.29	0.48	0.15	22.4
17b		7.7	351	310	14	399	3097	81	100	304	1008	457	831	83	147	-2.39	0.20	0.45	0.69	0.17	23.8
18a	Koelwar	7.8	224	213	55	553	2016	74	3	259	581	342	509	67	92	-2.68	-0.13	-0.09	0.53	0.17	23.8
18b		7.9	264	236	18	136	2589	56	14	251	724	342	470	73	107	-2.67	0.17	0.43	0.45	0.46	20.3

Units: Ionic concentrations in μM , except pH, EC ($\mu\text{S cm}^{-1}$), TDS (mg/l), SAR (meq l^{-1}) and RSC (meq l^{-1}), a = pre-monsoon, b = post-monsoon, EC = electrical conductivity, TDS = total dissolved solids, TH = total hardness, SIC and SID = saturation indices for calcite and dolomite, RSC = residual sodium carbonate, SAR = sodium adsorption ratio, DOS = Dehri on Son.

Table 1(b). Major ion chemistry of pre-monsoon 2013 and monsoon 2013 water samples used for flux and CDR calculation.

Location	Sampling period	pH	EC	TDS	F	Cl	HCO ₃	SO ₄	NO ₃	H ₄ SiO ₄	Ca	Mg	Na	K	Reference
Koelwar	Monsoon 2013 (August)	7	146	126	15.8	66	1327	34.4	19.8	169.3	437	193	196	23.5	This study
Koelwar	Pre-monsoon 2013 (April)	8	198	170	19.0	129	1655	69.2	11.8	223.7	640	308	365	34.3	This study
Koelwar	Monsoon 1982 (September)			129		71	1372	22		210	434	166	240	40	Sarin <i>et al.</i> (1989)
Koelwar	End monsoon 2006 (October)			170		116	1833	50.0	11	161	537	253	431	43.0	Rai <i>et al.</i> (2010)

Units: Concentration of major ions in μM , EC in $\mu\text{S cm}^{-1}$ and TDS in mg/l .

2950 μM in the pre-monsoon and 606–3737 μM during the post-monsoon season. On an equivalent basis, HCO_3^- alone accounts for 75% of the total anions (TZ⁻), followed by Cl^- (16.6%), SO_4^{2-} (5.7%), F^- (1.5%) and NO_3^- (0.8%). Chloride concentration varies from 56 to 6767 μM with an average value of 730.6 μM in pre-monsoon samples. The concentration of other measured anions in the pre-monsoon ranges between 2 and 820 μM for SO_4^{2-} , 3–89 μM for NO_3^- and 6–65 μM for F^- . In the post-monsoon, HCO_3^- accounts for 84% of the total anions, followed by Cl^- (8.2%), SO_4^{2-} (6.5%), NO_3^- (1.0%) and F^- (0.8%) in the equivalent unit. The concentration of Cl^- , SO_4^{2-} , NO_3^- and F^- in the post-monsoon varies from 43–2279, 10–844, 1–160 and 8–30 μM , respectively. Higher concentration of Cl^- in the river water was found at a few locations. In general, Cl^- concentration in river water does not exceed dissolved Na concentration. However, Cl^- can be found in excess of Na in river waters, which may be due to:

- (1) precipitation of Na as salts resulting in enrichment of Cl^- in water in arid and semi-arid climate (Sarin *et al.* 1989; Gaillardet *et al.* 1999),
- (2) contribution of very saline ground water (Gordeev and Sidorov 1993), and
- (3) anthropogenic contributions (Rai *et al.* 2010). Significant contribution of Cl^- from anthropogenic activities (effluent discharge) has been reported by Rai *et al.* (2010) for the Ganga River.

In the Son River water, higher Cl^- concentration can be attributed to anthropogenic activities at Diapiper located downstream of a major urban site (Shadol) and dissolution of the precipitated Na salts in soils, resulting in elevated Cl^- concentration during pre-monsoon. The precipitation of sodium carbonate minerals such as trona ($\text{Na}_2\text{CO}_3 \cdot \text{NaHCO}_3 \cdot 2\text{H}_2\text{O}$) and minor thermonarite ($\text{Na}_2\text{CO}_3 \cdot \text{H}_2\text{O}$) in alkaline soils of the Indo-Gangetic plains of India (Datta *et al.* 2002) can result in the enrichment of Cl^- in ground and river water. The oxidative weathering of pyrites associated with coal seams of Gondwanas (Singh and Hasnain 1999) and pyrites present within black shales of the Vindhyan Super Group (Banerjee *et al.* 2006) could be responsible for higher SO_4^{2-} values in the river water. The higher concentration of HCO_3^- indicates that significant chemical weathering has been occurring in the Son River catchment. Dissolved silica varies between 219 and 498 μM in pre-monsoon and between 153 and 433 μM in post-monsoon, which accounts for 9% of the TDS. The average concentration of dissolved silica (302.9 μM) is higher than the Indian average of 116.5 μM (Subramanian *et al.* 1987) and global average value of 179.7 μM (Meybeck *et al.* 1996).

A high concentration of dissolved silica in the Son River water reflects contribution from weathering of silicate rocks. The alkaline nature of river water enhances the solubility of silica and favours release of silica into solution during silicate weathering (Krauskopf 1959). Major cations constitute around 23% of the total dissolved loads. Ca^{2+} and Mg^{2+} are the dominant cations accounting for 52 and 25% of the total cations charge balance (TZ^+), respectively. Concentration of Ca^{2+} ranges from 220 to 3640 μM during the pre-monsoon and 175–1312 μM in the post-monsoon, with an average value of 743.6 μM and 698.6 μM , respectively. Na^+ concentration varies between 113 and 4167 μM (average 674.2 μM) and 91 and 1827 μM (average 517.6 μM) in the pre- and post-monsoon seasons, respectively. The concentration of Mg^{2+} and K^+ in the pre-monsoon varies from 99 to 876 μM and 5–312 μM , and from 95 to 518 μM and 27–127 μM in the post-monsoon, respectively.

Table 2 summarizes the average chemical composition of the Son River, some selected Indian rivers and average values of Indian and global rivers. TDS and HCO_3^- values of the Son River water is significantly higher than those of the Indian and world averages, while Ca^{2+} , Mg^{2+} , Na^+ , K^+ , Cl^- and SO_4^{2-} values are nearly equal to the Indian average but much higher than the world average (table 2). The higher concentration of dissolved silica of the Son River than those of Indian and world average is attributed to contribution from silicate weathering in the drainage basin.

4.2 Seasonal and spatial variations in major ions

Spatial and temporal variations in physical and chemical parameters are important for the assessment of factors controlling surface water composition. Figure 2 shows the seasonal variations of average concentration of measured parameters in

the Son River water. The average pH is slightly higher in the pre-monsoon season than in the post-monsoon season. The low values of EC and TDS during post-monsoon and higher values in the pre-monsoon period are common phenomena which indicate an increased concentration of major ions during the pre-monsoon period. Calcium, Na^+ , Cl^- , F^- and dissolved silica follow a similar trend as EC and TDS, i.e., higher concentration in the pre-monsoon which decreases in the post-monsoon period (table 1a). Seasonal variations in the concentration of dissolved constituents in the Son River can be attributed to evaporation effect or contribution from ground water during the lean flow period in the pre-monsoon and dilution effects of atmospheric precipitation in the post-monsoon season (Singh and Hasnain 1999). The ground water inherits ions during mineral–water interaction in the soil/sediment deposits. The average concentration of bicarbonate and nitrate shows slightly higher values during post-monsoon (2155 and 24.2 μM) as compared to pre-monsoon (1955 and 11.29 μM). The increase in HCO_3^- concentration can be attributed to seasonal variability in chemical weathering of carbonate and silicate minerals (Tipper *et al.* 2006) or redissolution of precipitated salt in the post-monsoon season induced by rain water and water level rise (Rengarajan *et al.* 2009). However, increase in NO_3^- concentration may be attributed to degradation of organic matter and/or anthropogenic sources including runoff from surrounding agricultural fields and untreated sewage (Sharma and Subramanian 2008). There is no significant variation in the concentration of Mg^{2+} , K^+ and SO_4^{2-} , reflecting their conservative behaviour in the basin.

The lowest concentrations of dissolved ions are found near the origin of the river at the Amarkantak site. No specific trend of spatial or downstream variation is observed in this study except increase

Table 2. Average composition of Son River water and its comparison with other river basins.

Rivers	HCO_3^-	Cl	SO_4	Silica	Ca	Mg	Na	K	TDS	Reference
Son	125	18	10	18	29	8	14	3	227	This study
Damodar	94	11	21	22	15	9	16	4	191	Singh and Hasnain (1999)
Krishna	178	38	49	24	29	8	30	2.4	360	Ramesh and Subramanian (1988)
Cauvery	135	20	13	23	21	9	43	4	272	Ramanathan <i>et al.</i> (1994)
Godavari	105	17	8	10	22	5	12	3	181	Biksham and Subramanian (1988)
Mahanadi	122	23	3	17	24	13	14	8.3	224	Chakrapani and Subramanian (1990)
Indus	64	9	15	5	27	1	1	2.1	122	Subramanian (1983)
Ganges	128	10	11	18	25	8	11	3	214	Subramanian (1983)
Brahmaputra	38	15	10	7	29	7	12	2.5	148	Subramanian (1983)
Narmada	225	20	5	9	14	20	27	2	322	Subramanian (1983)
Indian avg.	74	15	13	7	30	7	12	3	159	Subramanian (1983)
World avg.	62	4	9	12	16	4	4	1.5	115	Sarin <i>et al.</i> (1989)

Units: Ionic concentrations in mg l^{-1} .

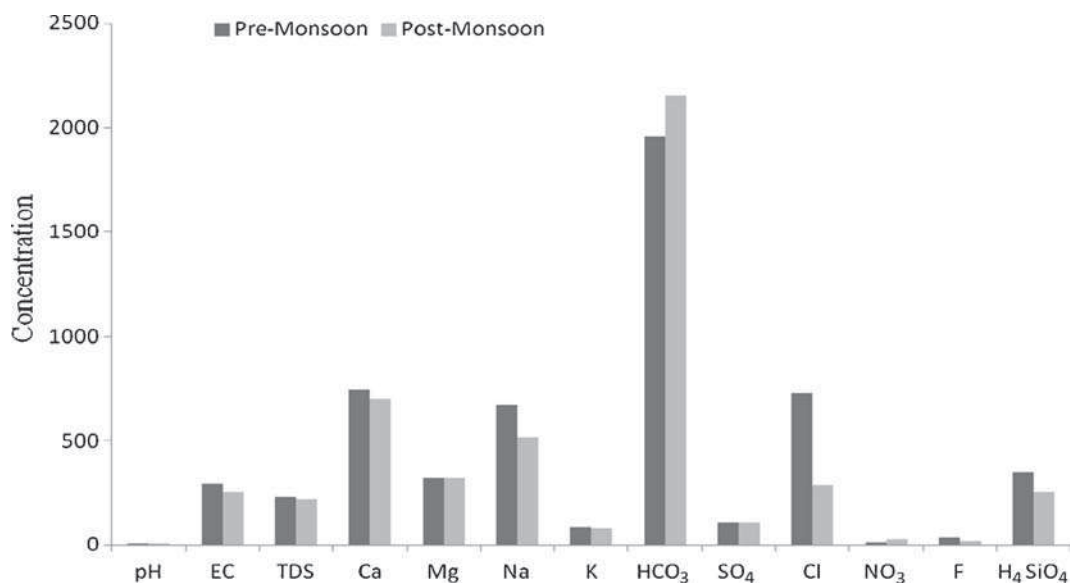


Figure 2. Seasonal variations in the concentration of measured parameters. All parameters except pH, EC ($\mu\text{S}/\text{cm}$) and TDS (mg/l) are in μM .

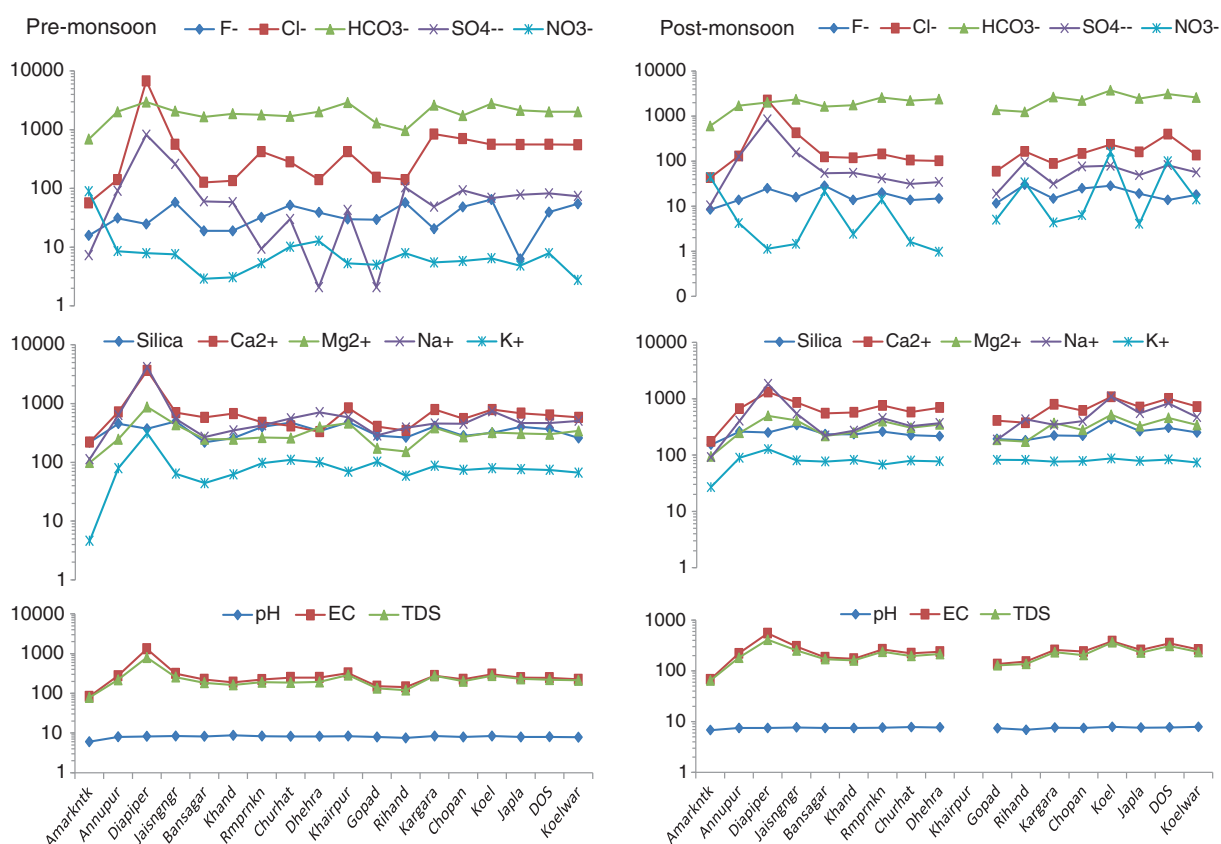


Figure 3. Spatial variations in the concentration of measured parameters (Ca^{2+} , Mg^{2+} , Na^{+} , K^{+} , H_4SiO_4 , F^{-} , Cl^{-} , HCO_3^{-} , SO_4^{2-} and NO_3^{-} in μM , EC in $\mu\text{S}/\text{cm}$ and TDS in mg/l).

in concentrations of TDS, Cl^{-} , SO_4^{2-} , Ca^{2+} , Na^{+} and K^{+} at sites 3 and 15, and decrease at sites 6, 11 and 12 (figure 3). The observed spatial variations in solute concentration could be related to the effects of tributaries inflow, changes in lithology,

anthropogenic inputs and presence of reservoirs/dams upstream. The observed higher concentration of most of the dissolved species at site 3 (Diapiper) may be attributed to very sluggish river flow, contributions from ground water and

anthropogenic activities. Decrease in ionic concentrations at sites 6 and 12, i.e., downstream reservoirs, indicate dilution effects of the Bansagar and Rihand reservoirs, constructed on the Son and Rihand Rivers, respectively.

4.3 Weathering and solute acquisition processes

Chemical weathering of rocks in the catchment area plays an important role in determining the nature and amount of dissolved load carried by rivers. Therefore, dissolved components of rivers become important to characterize the nature and extent of weathering in the drainage basin. The nature of weathering is mainly controlled by lithology, tectonics, vegetation and climate of the drainage basin. However, secondary contribution from atmospheric and anthropogenic sources can also contribute to the chemistry of river water (Meybeck 2005).

Major natural processes determining major ion chemistry of water can be identified by plotting the variations in weight ratios of $\text{Na}^+ + \text{K}^+ / (\text{Na}^+ + \text{K}^+ + \text{Ca}^{2+})$ as a function of the TDS (Gibbs 1970). The plotting of most of the samples in the field of 'weathering dominance' suggests rock weathering as the major mechanism controlling the water composition of the Son River (figure 4). In general, HCO_3^- , Ca^{2+} and Mg^{2+} in river water are almost entirely derived from rock weathering (Berner and Berner 1987). The plotted points of the majority of the Son River

water samples on the variation diagram relating $(\text{Ca}^{2+} + \text{Mg}^{2+})$ and $(\text{HCO}_3^- + \text{SO}_4^{2-})$ fall along the 1:1 equiline (figure 5a). This may be due to the dissolution of calcite, dolomite and gypsum as the major process in the system (Cerling et al. 1989; Fisher and Mullican 1997). The stoichiometry of carbonate weathering reaction demands that carbonate derived Ca^{2+} and Mg^{2+} should be equal to the carbonate derived bicarbonate (HCO_3^-). The analysis shows that in the Son River water HCO_3^- is slightly enriched than total Ca^{2+} and Mg^{2+} as shown in (figure 5b). The above finding suggests that carbonate weathering could be a major contributor for Ca^{2+} , Mg^{2+} and HCO_3^- in the Son River water. Further, the variation plot of $\text{Ca}^{2+} + \text{Mg}^{2+}$ vs. TZ^+ shows that plotted points fall just below the equiline, indicating significant contribution from Ca^{2+} and Mg^{2+} to the total cations (TZ^+) balance, which is also reflected by higher $\text{Ca}^{2+} + \text{Mg}^{2+} / \text{TZ}^+$ equivalent ratio, i.e. 0.77 (figure 5c). The deviation of plotted points from the equiline at higher concentration indicates an increasing contribution of Na^+ and K^+ from silicate weathering or saline/alkaline soil (Rai et al. 2010). It can be suggested that a significant portion of the major ions are probably derived from the weathering of carbonates (dolomites, lime stones) of Vindhyan and silicates rocks (sandstone, shale and volcanoclastics) of Gondwanas, Vindhyan and Mahakoshal group in the Son River basin.

The average Na^+ concentration in the Son River water is significantly higher than chloride. Higher $\text{Na}^+ + \text{K}^+ / \text{Cl}^-$ equivalent ratio (average 2.68) suggests that much of the alkalis ($\text{Na}^+ + \text{K}^+$) in the Son River water originates from non-atmospheric sources (figure 5d). The $\text{Na}^+ + \text{K}^+ / \text{TZ}^+$ ratio can also be used as an index to evaluate the contribution of cations through silicate weathering (Stallard and Edmond 1983). The plot of $\text{Na}^+ + \text{K}^+$ vs. TZ^+ and $\text{Na}^+ + \text{K}^+ / \text{TZ}^+$ ratio (0.23) suggest contribution of Na^+ and K^+ to the dissolved ions from the weathering of silicates (figure 5e). K^+ is the least dominant cation and almost constant throughout the drainage basin. Adsorption of K^+ ions with the clay minerals seems to be controlling the conservative behaviour of potassium. During continental weathering Na^+ is more mobile than K^+ and therefore dominant in the natural solutions (Milliot 1970).

A characteristic feature for rivers with prevailing carbonate weathering in their drainage basin is the predominance of Ca^{2+} and Mg^{2+} cations and high $\text{Ca}^{2+} + \text{Mg}^{2+} / \text{Na}^+ + \text{K}^+$ ratios. Most of the world's rivers and the major Indian rivers have high $\text{Ca}^{2+} + \text{Mg}^{2+} / \text{Na}^+ + \text{K}^+$ ratios, suggesting weathering of carbonate rocks in the catchment area (Subramanian 1979). The $\text{Ca}^{2+} + \text{Mg}^{2+} / \text{Na}^+ + \text{K}^+$ molar abundance ratio in silicates of the upper

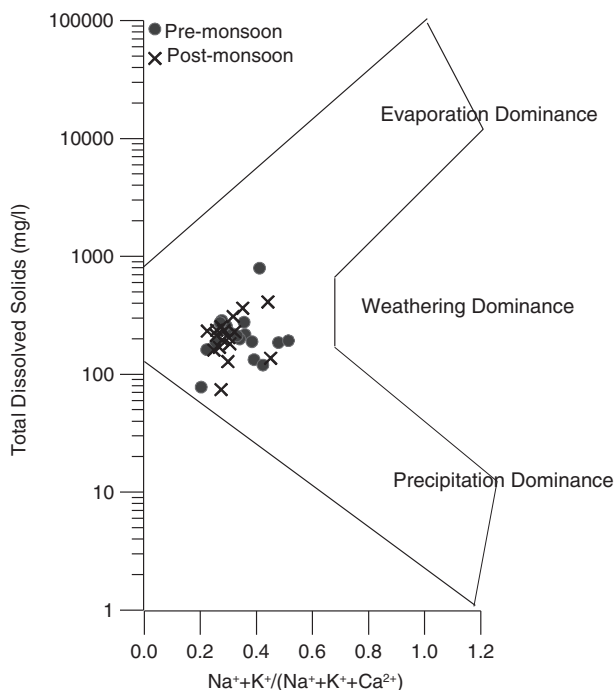


Figure 4. Variation of the weight ratio of $\text{Na}/(\text{Na} + \text{Ca})$ as a function of TDS (after Gibbs 1970).

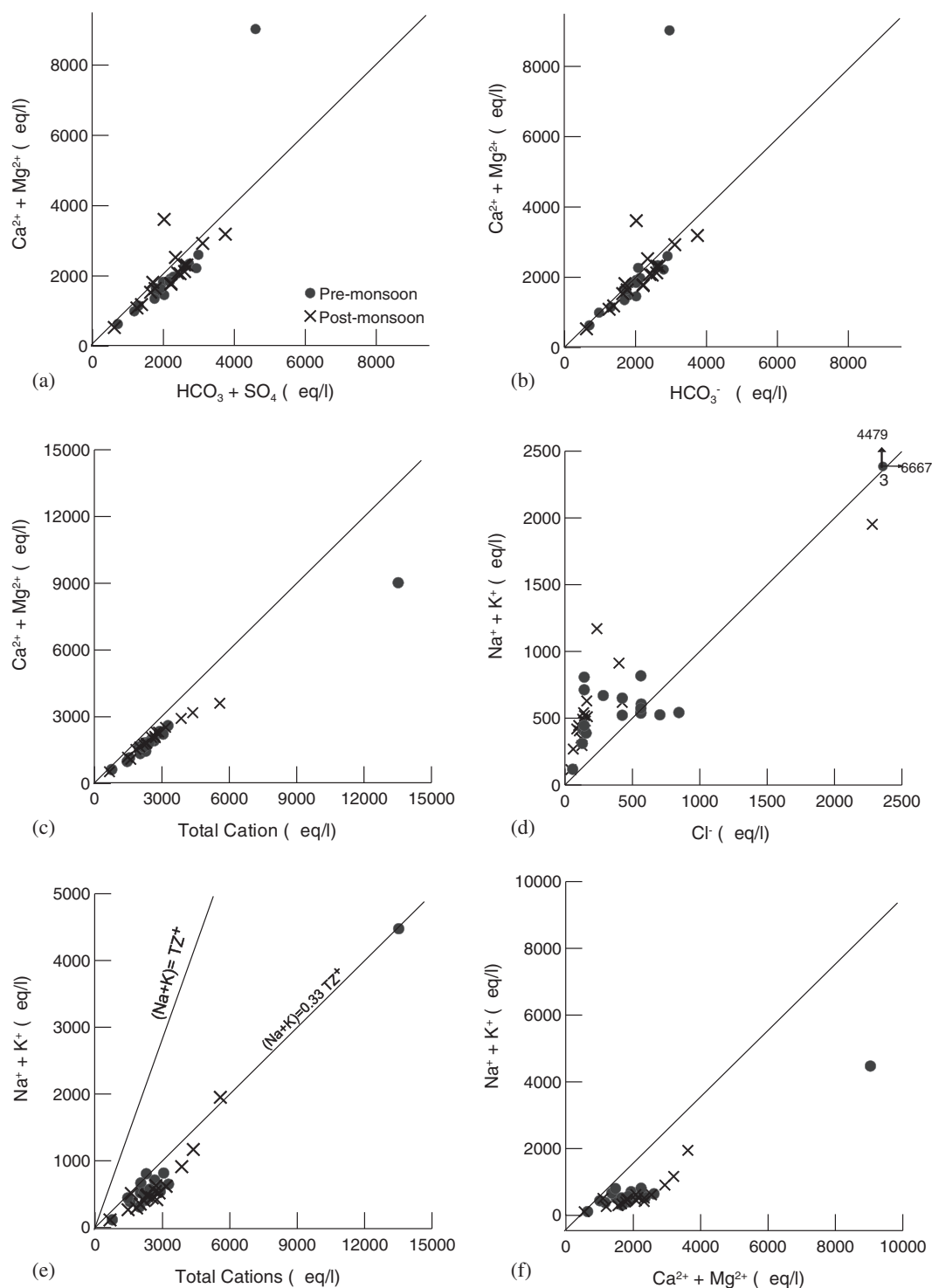


Figure 5. Scatter plots between (a) $\text{Ca}^{2+} + \text{Mg}^{2+}$ vs. $\text{HCO}_3^- + \text{SO}_4^{2-}$, (b) $\text{Ca}^{2+} + \text{Mg}^{2+}$ vs. HCO_3^- , (c) $\text{Ca}^{2+} + \text{Mg}^{2+}$ vs. TZ^+ , (d) $\text{Na}^+ + \text{K}^+$ vs. Cl^- , (e) $\text{Na}^+ + \text{K}^+$ vs. TZ^+ , and (f) $\text{Na}^+ + \text{K}^+$ vs. $\text{Ca}^{2+} + \text{Mg}^{2+}$.

crust is generally 1.0 (Taylor and McLennan 1985). The average $\text{Ca}^{2+} + \text{Mg}^{2+}/\text{Na}^+ + \text{K}^+$ ratio for the Son River is found to be 3.61, higher than the world (2.2) and the Indian river average (2.5), suggesting that the chemical composition of the Son River is principally controlled by weathering of carbonates (figure 5f). Rai *et al.* (2010) have reported higher

carbonate weathering rate than silicate weathering for the Son River on the basis of their study on tail-end monsoon samples. Our study supports the same for both pre-monsoon and post-monsoon seasons.

The correlation matrix data of major ions and other parameters also substantiate the above

Table 3. Inter-elemental correlation of geochemical parameters in the Son River water.

	pH	EC	TDS	F	Cl	HCO ₃	SO ₄	NO ₃	H ₄ SiO ₄	Ca	Mg	Na	K	TH
Pre-monsoon														
pH	1.00													
EC	0.24	1.00												
TDS	0.32	0.98	1.00											
F	0.15	-0.09	-0.06	1.00										
Cl	0.13	0.98	0.95	-0.12	1.00									
HCO ₃	0.65	0.59	0.70	0.02	0.48	1.00								
SO ₄	0.14	0.95	0.92	-0.02	0.95	0.43	1.00							
NO ₃	-0.88	-0.17	-0.24	-0.23	-0.09	-0.50	-0.11	1.00						
H ₄ SiO ₄	0.64	0.26	0.34	0.18	0.13	0.61	0.17	-0.57	1.00					
Ca	0.22	0.98	0.97	-0.16	0.98	0.58	0.95	-0.16	0.19	1.00				
Mg	0.42	0.91	0.95	-0.02	0.86	0.77	0.84	-0.30	0.43	0.88	1.00			
Na	0.17	0.99	0.96	-0.06	0.98	0.51	0.94	-0.12	0.18	0.97	0.87	1.00		
K	0.31	0.93	0.91	-0.05	0.92	0.51	0.85	-0.29	0.32	0.90	0.83	0.94	1.00	
TH	0.26	0.99	0.98	-0.13	0.97	0.62	0.94	-0.19	0.24	0.99	0.92	0.97	0.90	1.00
Post-monsoon														
pH	1.00													
EC	0.54	1.00												
TDS	0.61	0.98	1.00											
F	0.02	0.34	0.35	1.00										
Cl	0.03	0.79	0.68	0.27	1.00									
HCO ₃	0.84	0.64	0.76	0.22	0.05	1.00								
SO ₄	-0.00	0.75	0.63	0.29	0.98	-0.01	1.00							
NO ₃	0.12	0.23	0.36	0.28	-0.06	0.48	-0.12	1.00						
H ₄ SiO ₄	0.27	0.36	0.45	0.04	0.06	0.48	0.02	0.73	1.00					
Ca	0.64	0.97	0.98	0.29	0.67	0.74	0.63	0.28	0.41	1.00				
Mg	0.73	0.91	0.95	0.24	0.50	0.87	0.43	0.35	0.48	0.95	1.00			
Na	0.28	0.94	0.90	0.41	0.88	0.44	0.85	0.31	0.35	0.87	0.76	1.00		
K	0.39	0.75	0.69	0.41	0.70	0.33	0.72	-0.07	-0.11	0.72	0.57	0.74	1.00	
TH	0.67	0.96	0.98	0.28	0.63	0.79	0.58	0.31	0.44	0.99	0.97	0.84	0.68	1.00

inference (table 3). The observed good correlation between cations, i.e., Ca–Mg (pre-monsoon: 0.88, post-monsoon: 0.95), Ca–Na (pre-monsoon: 0.97, post-monsoon: 0.87), Ca–K (pre-monsoon: 0.90, post-monsoon: 0.72) and Na–K (pre-monsoon: 0.94, post-monsoon: 0.74) suggests a common source for cations. HCO₃⁻ has a strong correlation with Ca²⁺ and Mg²⁺ and good to fair correlation with Na⁺ and K⁺ reflecting the dissolution of carbonates and weathering of silicates within the basin. The strong correlation of EC with all major ions (except F⁻ and NO₃⁻) due to significant amount of dissolved salt is observed at all sites. Chloride and sulphate show good correlation with each other and also with calcium, magnesium, sodium and potassium indicating a common source, which can be due to dissolution of salts, remobilisation of ions from saline/alkaline soils and/or anthropogenic input (Rengarajan *et al.* 2009). The moderate correlation between HCO₃⁻ and NO₃⁻ during post-monsoon suggesting

ground water degradation of organic matter or anthropogenic activities as probable sources.

The Piper (1944) diagram is very useful in determining relationships of different dissolved constituents and classification of water on the basis of its chemical character. The triangular cationic fields of Piper diagram reveals that most of the plotted points of the water samples fall into Ca²⁺, some in Mg²⁺ and few in no dominant zone, whereas in the anion triangle majority of the samples fall into bicarbonate field. The plot of chemical data on diamond shaped central field reveals the dominance of alkaline earth metals (Ca²⁺+Mg²⁺) over alkali metal cations (Na⁺+K⁺) and weak acid (HCO₃⁻) over strong acid (SO₄²⁻+Cl⁻) in the Son water (figure 6). Therefore, according to Back (1966), Ca–Mg–HCO₃ is the dominant hydrogeochemical facies except for a few samples (figure 3a and b) which plot in the Piper diagram (figure 6) as a mixed chemical character of Ca–Mg–Cl hydrogeochemical facies.

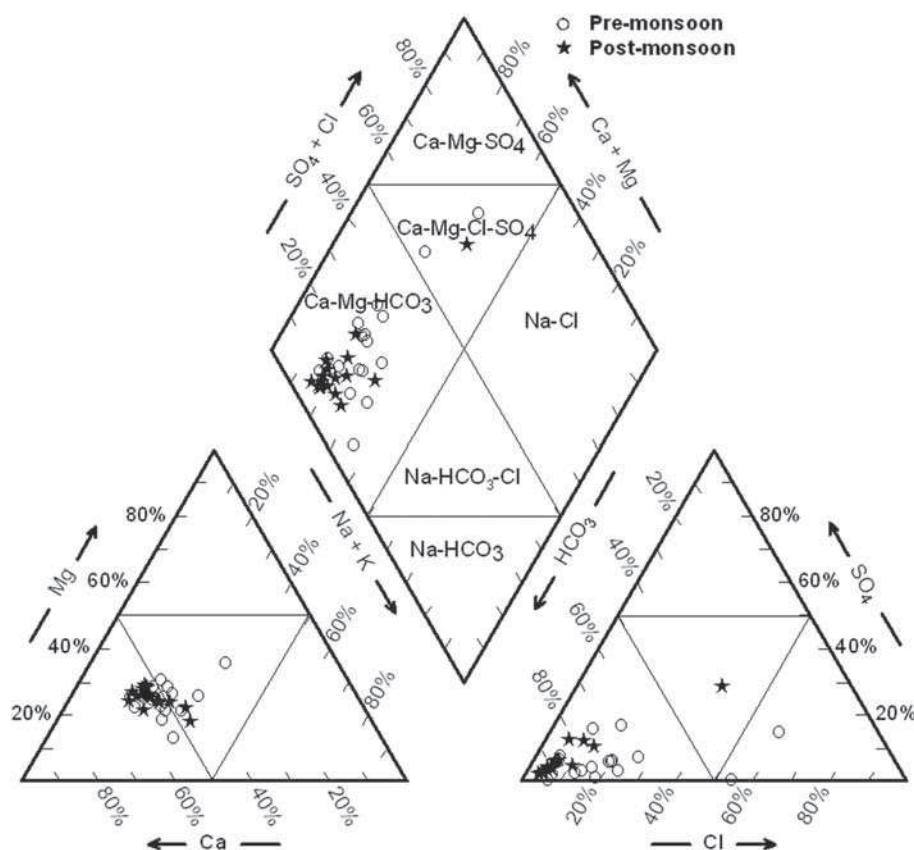


Figure 6. Piper trilinear diagram for hydrochemical facies of Son River water (after Piper 1944).

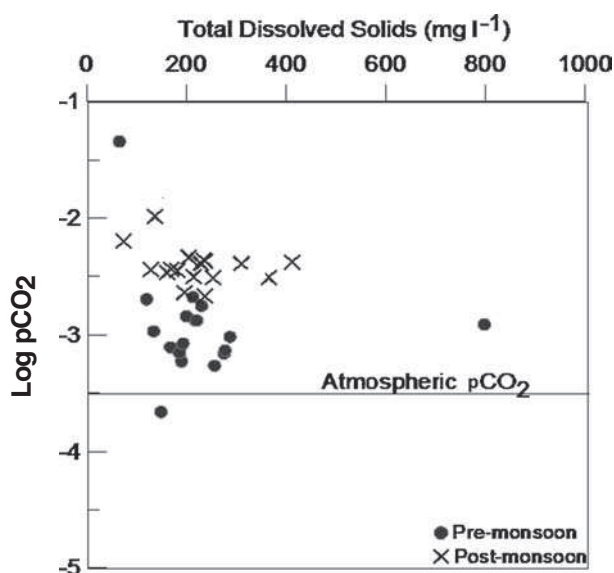


Figure 7. Relationship between $p\text{CO}_2$ and total dissolved solids (TDS).

The computed partial pressure $p\text{CO}_2$ (Garrels and Christ 1965) for the Son River water (table 1a) is slightly higher ($10^{-3.26}$ – $10^{-1.34}$) than the atmospheric level ($10^{-3.5}$), except one sample of the Bansagar reservoir (figure 7). The higher $p\text{CO}_2$ in the river

water is a global trend indicating that the rivers are commonly not in equilibrium with the atmosphere (Garrels and Mackenzie 1971). Slightly higher $p\text{CO}_2$ values could be attributed to significant contribution from CO_2 -rich groundwater to the river channel. The re-equilibration with the atmosphere is achieved by slow release of excess CO_2 (Holland 1978; Stumm and Morgan 1981). The equilibrium state of the water with respect to a mineral phase can be determined by calculating a saturation index (SI) using analytical data (Stumm and Morgan 1981). The plot of saturation index of calcite (SI_c) vs. dolomite (SI_d) demonstrate that most of the post-monsoon samples are in undersaturated condition, while majority of the pre-monsoon water samples are supersaturated with respect to both calcite and dolomite (figure 8). The supersaturation shows the evaporation effects during the lean water level period of the pre-monsoon, which favours precipitation of carbonates (Hardie and Eugster 1970).

4.4 Principal component analysis

The principal component analysis is useful in identifying and interpreting relations among different parameters of river water, reflecting the variance

of a large set of inter-correlated variables by condensing a larger data set into a smaller set of independent components with a minimum loss of original information (Bhardwaj *et al.* 2010). The principal component analysis for the Son River water is given in table 4. The data matrix of 14 parameters and 35 observations has been used in the present study. It shows that the first three principal components together accounts for 85.854% of the total variance in the dataset, in which the first principal component accounts for 61.746%,

second principal component accounts for 14.178% and the third principal component accounts for 9.930% of the total variance. Values of the communality for all variables (14) and the eigen values (>1) of the first three principal components can be applied to identify the dominant hydrogeochemical processes. In the first principal component, the values of EC, Cl^- , Na^+ , Ca^{2+} , TH, TDS, SO_4^{2-} , K^+ and Mg^{2+} show high positive loading, whereas values of HCO_3^- , H_4SiO_4 and pH have low positive loading. Fluoride and nitrate have very low to negative loading. The high positive loading of EC, Na^+ , Ca^{2+} , Mg^{2+} , K^+ , TH, TDS, Cl^- and SO_4^{2-} ions on the first principal component suggests that this component is associated with weathering and solute acquisition processes in the catchment.

The second principal component has high to moderate positive loading of pH, H_4SiO_4 , F^- , HCO_3^- and low positive loading of TDS and Mg^{2+} , while others have negative loading. The association of F^- and H_4SiO_4 in water may be due to the ionic exchange of F^- and OH^- on the clay minerals (Subba Rao and Devadas 2003). It also appears that the association of HCO_3^- , F^- and silica with pH seems to play a role here. The third principal component has high positive loading of NO_3^- and moderate positive loading of HCO_3^- , while others have low to negative loading. The covariance of bicarbonate and nitrate in the water can be attributed to a common source likely to be the ground water, affected by organic matter decomposition and/or anthropogenic activities (irrigation return flow/agricultural runoff, fertilizers and sewage).

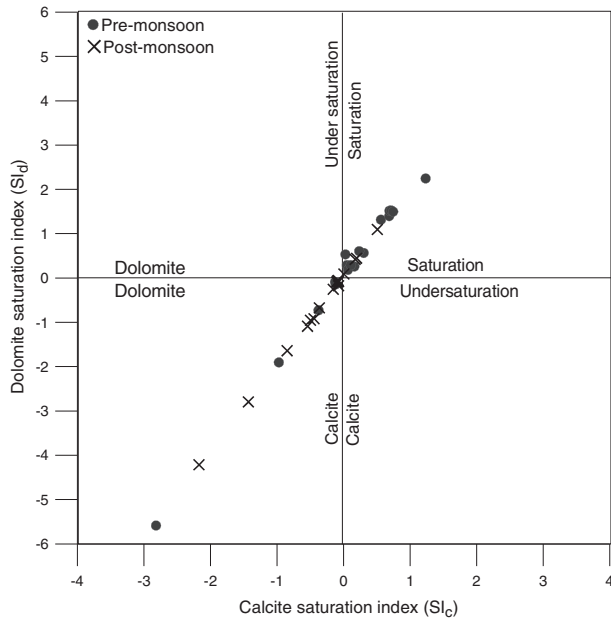


Figure 8. Plot of saturation indices (SI) of dolomite (SI_d) vs. calcite (SI_c).

Table 4. Principal and rotated component matrix.

Parameters	Principal component matrix			Communality	Rotated component matrix		
	I	II	III		I	II	III
EC	0.992	-0.091	-0.031	0.993	0.978	0.172	0.086
TDS	0.992	0.006	0.099	0.994	0.937	0.271	0.208
TH	0.986	-0.903	0.068	0.985	0.96	0.173	0.184
Ca	0.975	-0.15	0.024	0.973	0.97	0.113	0.142
Mg	0.926	0.14	0.23	0.93	0.822	0.387	0.322
Na	0.966	-0.163	-0.072	0.966	0.977	0.095	0.047
K	0.907	-0.076	-0.197	0.867	0.913	0.16	-0.089
Cl	0.927	-0.219	-0.225	0.959	0.973	0.026	-0.106
SO_4	0.808	-0.283	-0.27	0.807	0.881	-0.069	-0.160
HCO_3	0.587	0.389	0.592	0.846	0.388	0.55	0.627
H_4SiO_4	0.361	0.752	0.089	0.704	0.141	0.823	0.080
F	0.053	0.57	-0.383	0.474	-0.048	0.551	-0.411
NO_3	-0.019	-0.212	0.798	0.683	-0.063	-0.183	0.804
pH	0.386	0.823	-0.107	0.838	0.171	0.892	-0.117
Eigenvalues					8.644	1.985	1.39
Variance (%)					61.746	14.178	9.93
Cumulative % of variance					61.746	75.924	85.854

4.5 Dissolved fluxes and chemical denudation rate (CDR)

It is essential to estimate the elemental fluxes of rivers to understand the nature and extent of elemental dynamics from continent to river and ocean systems. This helps in quantifying the global riverine geochemical budget. Studies are available on fluvial mass transport by a number of researchers during past few decades with an attempt to quantify global riverine fluxes (Meybeck 1976; Martin and Meybeck 1979; Subramanian 1979, 1984; Hu *et al.* 1982; Sarin *et al.* 1989; Krishnaswami *et al.* 1992; Rai *et al.* 2010; Gupta *et al.* 2011; Yadav and Chakrapani 2011). An attempt has been made to estimate the average annual fluxes of dissolved major ions and chemical denudation rate (CDR) of the Son River basin. Here, we have used the discharge and drainage data reported by Rao (1975) for flux and CDR calculation. The data of Rao (1975) is used by this and other studies because of unavailability of discharge data for regulatory reasons. In earlier studies, the average annual (average of monsoon and non-monsoon months) discharge data of Rao (1975) and water chemistry of mainly monsoon season was used to quantify the flux, which ultimately have given monsoon biased results. Again, the discharge during monsoon and non-monsoon varies for different river basins depending upon the sources (glacial/non-glacial) and interannual variability of precipitation. Here, we have adopted an approach similar to that of Sarin and Krishnaswami (1984) for flux and CDR calculation. Rao (1975) has reported that most of the water discharge occurs during the monsoon (>90%) and the rest during the non-monsoon seasons (>10%). Therefore, for the calculation of flux and CDR we have given 90% weightage to monsoon and 10% to non-monsoon, i.e. pre-monsoon and post-monsoon seasons for the annual average discharge. Chemical composition of non-monsoon (average of pre-monsoon 2013 and post-monsoon 2010, assuming that not much change has occurred during this period) and monsoon-2013 samples are used for flux and CDR calculation (table 1b). The calculated annual fluxes of major ions, total solute flux and CDR of the Son River along with some other rivers of the Ganga basin are given in table 5. The Son River annually delivers 4.2 million tons of dissolved loads at Koelwar with 3.6 million tons yr^{-1} during monsoon and 0.6 million tons yr^{-1} during non-monsoon seasons, respectively. The chemical denudation rate of the Son River basin is estimated at 59.5 tons $\text{km}^{-2} \text{yr}^{-1}$ with a value of 50.5 tons $\text{km}^{-2} \text{yr}^{-1}$ during monsoon and 9 tons $\text{km}^{-2} \text{yr}^{-1}$ in non-monsoon seasons. The present estimation of flux and CDR is without correction

Table 5. Dissolved and solute flux and chemical denudation rate of the Son (at Koelwar) and selected rivers.

Rivers	Discharge	Area	Na*	K*	Mg*	Ca*	HCO ₃ *	Cl*	SO ₄ *	NO ₃ *	F*	SiO ₂ *	TDS Δ	CDR \diamond	Reference
Son	31.8	71.3	6.9	0.8	6.5	14.7	44.7	2.3	1.2	0.6	0.5	5.6	4.2	59.5	This study
Son	32		8.9	1.4	6.1	15	48	3	0.9			6.9	4.5	63.3	Sarin and Krishnaswami (1984)
Son	31.8	71.3											6	96	Subramanian (1984)
Son	31.8	71.3	13.7		8	17.1	58	3.7	1.6			5.1	5.4	75.8	Rai <i>et al.</i> (2010)
Gomti	7.4	30.4	10.4		6.3	6.4	32	2.4	1.5			0.7			Rai <i>et al.</i> (2010)
Ghagra	94.4	128	24.2		36.2	81.8	241	4.1	12.4			9.6			Rai <i>et al.</i> (2010)
Gandak	52.2	46.3	7.2		16.1	37.2	100	2	9.8			4.8			Rai <i>et al.</i> (2010)
Kosi	62	74.5	10.7		10.3	26.1	78	0.9	4.2			7.1			Rai <i>et al.</i> (2010)
Yamuna	93	366	118.6		41.2	62.6	239	64.7	16.8			12			Rai <i>et al.</i> (2010)
Ganga	380	935	126.9		103.7	269.4	802	35.7	36.5			28.5			Rai <i>et al.</i> (2010)
Yamuna	93	140	80	6	26	55	198	33	10			16	20	143	Sarin <i>et al.</i> (1989)
Ganga	393	975	172	27	113	249	819	55	35			54	70	72	Sarin <i>et al.</i> (1989)
World avg.	31400	101000	6000	1200	5200	12500	32000	3300	3000			6500	3600	36	Hu <i>et al.</i> (1982)

Note: Discharge: $10^{12} \text{ l yr}^{-1}$, area: 10^3 km^2 , *: 10^9 moles yr^{-1} , Δ : million tons yr^{-1} , \diamond : tons $\text{km}^{-2} \text{yr}^{-1}$.

for atmospheric input, as the atmospheric input is negligible during the study period as discussed earlier in section 4.3. Thus, the variation in dissolved fluxes and CDR values during monsoon and non-monsoon periods highlight the importance of water discharge and measured concentration of various elements, which is controlled by differential weathering behaviour of various lithologies, seasonal variations in evaporation, precipitation and/or dissolution of minerals/salts, ground water contribution and anthropogenic activities in different seasons.

The dissolved flux data of the Son River reflect that the river contributes a total of $\sim 6\%$ (4.2 million tons yr^{-1}) of the dissolved load transported by the Ganga river (70 million tons yr^{-1} ; Sarin *et al.* 1989) to the Bay of Bengal, while the drainage area and water discharge of the Son is, respectively, 7% and 8% of that of the Ganga River. The contribution of individual ionic species to total dissolved flux by the Son River are as follows: Na^+ (8%), K^+ (1%), Mg^{2+} (8%), Ca^{2+} (17.5%), HCO_3^- (53%), Cl^- (3%), SO_4^{2-} (1.4%), F^- (0.6%), NO_3^- (0.7%) and H_4SiO_4 (7%). The annual average major ion fluxes, total solute load and CDR of the Son River show lower values compared to the result of Rai *et al.* (2010) and Sarin *et al.* (1989). This difference can be ascribed to the different approaches adopted by authors to calculate flux and CDR, and to the yearly or seasonal variation in the concentration of dissolved ions. However, comparison of the measured concentration of dissolved ions with that of Rai *et al.* (2010) and Sarin *et al.* (1989) does not show much difference during monsoon season (table 1b). Our study emphasizes the importance of the methodology/approach used for flux and CDR estimation.

4.6 Water quality assessment

The parameters such as sodium absorption ratio (SAR), percent sodium (%Na) and residual sodium carbonate (RSC) were estimated to assess the suitability of the Son River water for irrigation purpose (table 1a). EC and Na concentration are very important in classifying irrigation water. The total concentration of soluble salts in irrigation water can be expressed for the purpose of classification of irrigation water as low ($\text{EC} \leq 250 \mu\text{S cm}^{-1}$), medium ($250\text{--}750 \mu\text{S cm}^{-1}$), high ($750\text{--}2250 \mu\text{S cm}^{-1}$) and very high ($2250\text{--}5000 \mu\text{S cm}^{-1}$) salinity zones (Wilcox 1955). Irrigation water with a high salt concentration results in the formation of saline soil, whereas a high sodium concentration leads to development of alkaline soil. The sodium or alkali hazard occurrence is determined by the absolute and relative concentration of cations and expressed in terms of sodium absorption ratio (SAR).

On the basis of SAR value, water can be classified as low ($\text{SAR} < 6$), medium (6–12), high (12–18) and very high (>18) alkali water. The calculated value of SAR in the study area varies from 0.20 to 1.96 in the pre-monsoon and 0.17 to 1.36 in the post-monsoon periods. The plot of data on the US salinity diagram in which the EC is taken as salinity hazard and SAR as alkalinity hazard shows that most of the surface water samples fall in the category C1S1 and C2S1 (Richards 1954), indicating low to medium salinity and low sodium water, which can be used for irrigation with little danger of development of exchangeable sodium and salinity (figure 9).

Sodium concentration is important in classifying irrigation water because sodium reacts with soil to reduce its permeability. Excess sodium in water produces undesirable effects of changing soil properties and reducing soil permeability (Kelley 1951). The %Na of the surface water in the study area ranges between 15.7 and 35.6 in the pre-monsoon and between 15.4 and 35.1 in the post-monsoon. According to Bureau of Indian Standard (BIS 2004), maximum percent sodium of 60% is recommended for irrigation water. A plot of analysed data on the Wilcox (1955) diagram relating EC and %Na shows that the water is good to excellent for irrigation (figure 10).

The quantity of bicarbonate and carbonate in excess of alkaline earths ($\text{Ca}^{2+} + \text{Mg}^{2+}$) also influence the suitability of water for irrigation purposes. When the sum of CO_3^{2-} and HCO_3^- is excess over

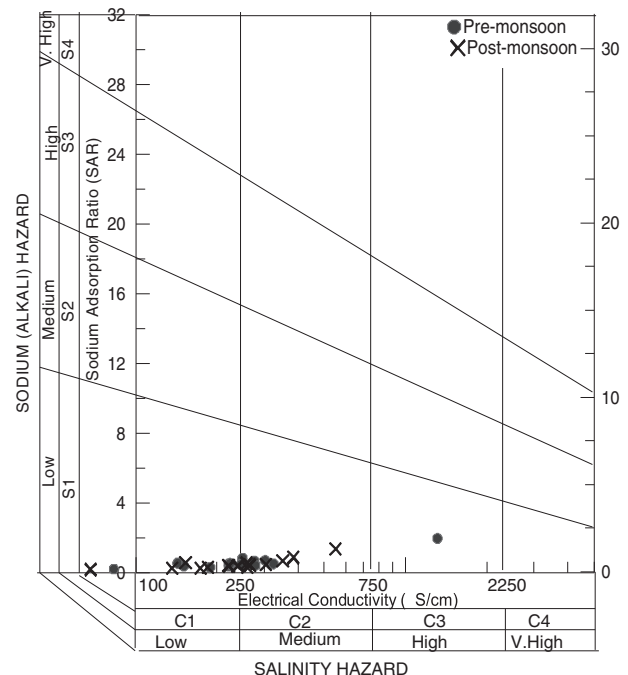


Figure 9. USSS salinity diagram of Son River water for classification of irrigation water (after Richards 1954).

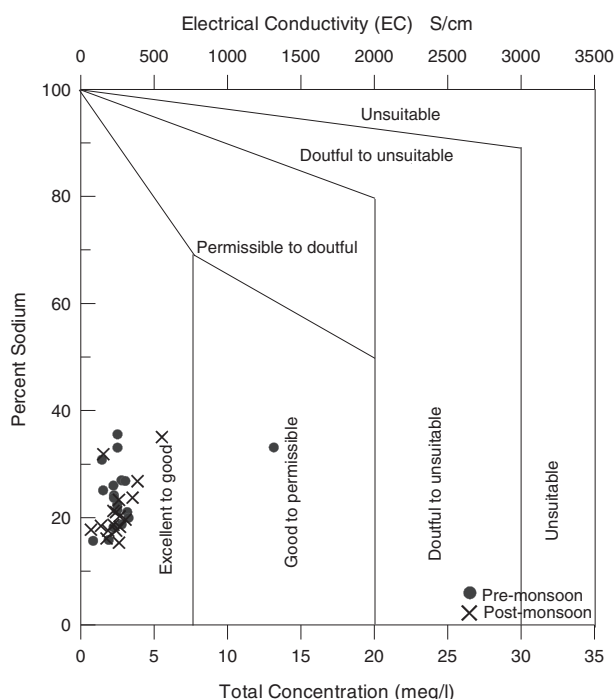


Figure 10. Wilcox diagram for classification of Son River water based on EC and %Na (after Wilcox 1955).

Ca^{2+} and Mg^{2+} , there may be possibility of complete precipitation of Ca^{2+} and Mg^{2+} as carbonates (Karanth 1989). The effects of carbonate and bicarbonate can be assessed by estimating residual sodium carbonate ($\text{RSC} = \text{CO}_3^{2-} + \text{HCO}_3^- - \text{Ca}^{2+} + \text{Mg}^{2+}$, all concentration in meq/l). A high value of RSC in water leads to an increase in the adsorption of sodium on soil (Eaton 1950). Irrigation water having RSC values greater than 5 meq l^{-1} has been considered harmful to the growth of plants, while waters with RSC values above 2.5 meq l^{-1} is not suitable for irrigation purpose. The RSC value of the Son River water samples varies from -6.08 to 0.58 meq l^{-1} in pre-monsoon and -1.60 to 0.55 meq l^{-1} in post-monsoon season. The low RSC (<1.25 meq l^{-1}) values suggest that the Son River water is safe and suitable for irrigation uses. Also to assess the suitability for drinking water purposes, the measured hydrochemical parameters of the Son River water were compared with guidelines values of WHO (2004) and BIS (2004), which shows that values are within the maximum permissible limit and suitable for drinking purposes.

5. Conclusions

The present study shows that the Son River water is alkaline in nature, and Ca^{2+} , Mg^{2+} and HCO_3^- are the predominant dissolved ions. The water chemistry is primarily controlled by

rock weathering with secondary contributions from ground water, saline/alkaline soils and anthropogenic sources. The chemical composition of Son River water reflects the influence of both carbonate and silicate weathering, with the dominance of carbonate dissolution in controlling the water chemistry. The Son River water is supersaturated with respect to calcite and dolomite in the pre-monsoon and undersaturated in the remaining seasons of the year. The higher concentration of most of the measured parameters at Diapiper reflects the impact of anthropogenic activities.

The Son River delivers about 4.2 million tons of dissolved loads annually to the Ganga River, which accounts for $\sim 6\%$ of the total annual load carried by the Ganga River to the Bay of Bengal. The Son River has lower solute flux, but higher CDR (59.5 tons $\text{km}^{-2} \text{yr}^{-1}$) compared to the world average (36 tons $\text{km}^{-2} \text{yr}^{-1}$). Values of solute flux and CDR during non-monsoon and post-monsoon highlight a strong seasonal control. The difference observed for the values of solute flux and CDR of the Son River between the present and earlier studies shows the importance of the methodology adopted for flux and CDR estimation. The measured hydrochemical parameters, sodium adsorption ratio (SAR), percent sodium (%Na) and residual sodium carbonate (RSC) indicate that Son River water is good to excellent in quality for irrigation and also can safely be used for drinking purposes. The study provides an insight into the contribution of small/medium size river to a large river system, with a need to investigate their role in a more detailed and systematic way.

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