

## Major ion chemistry of the Ganga source waters: Weathering in the high altitude Himalaya

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**Abstract.** A systematic study of the major ion chemistry of the Ganga source waters—the Bhagirathi, Alaknanda and their tributaries—has been carried out to assess the chemical weathering processes in the high altitude Himalaya. Among major ions, Ca, Mg, HCO<sub>3</sub> and SO<sub>4</sub> are the most abundant in these river waters. These results suggest that weathering of carbonate rocks by carbonic and sulphuric acids dominates in these drainage basins. On an average, silicate weathering can contribute up to ~30% of the total cations.

The concentration of total dissolved salts in the Bhagirathi and the Alaknanda is 104 and 115 mg/l, respectively. The chemical denudation rate in the drainage basins of the Bhagirathi and the Alaknanda is, respectively, 110 and 137 tons/km<sup>2</sup>/yr, significantly higher than that derived for the entire Ganga basin, indicating intense chemical erosion of the Himalaya.

**Keywords.** Major ions; dissolved salts; rivers; chemical weathering; chemical denudation rate.

### 1. Introduction

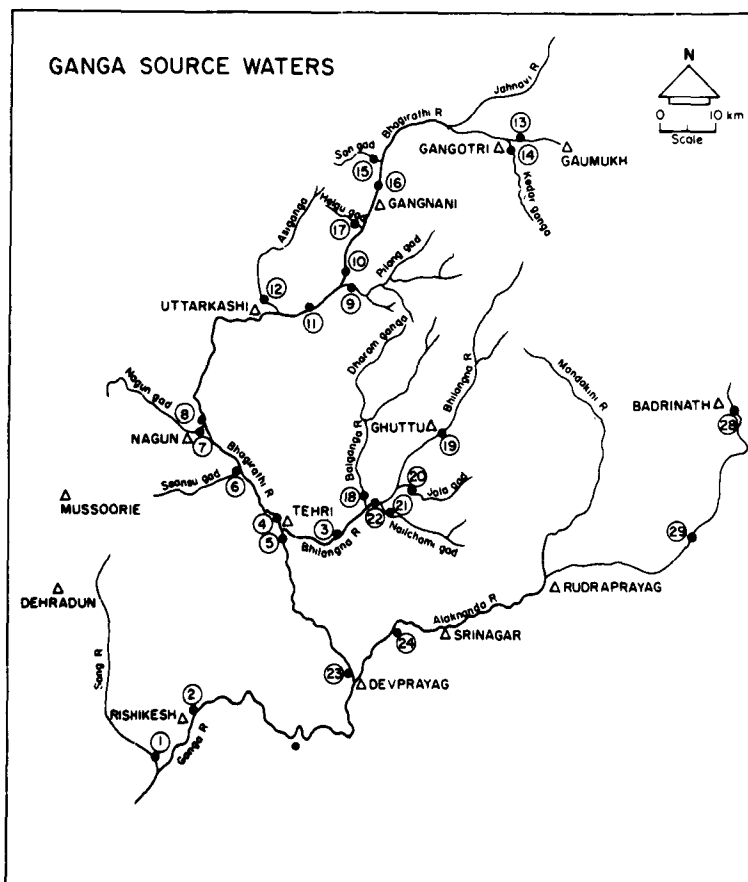
In one of our recent papers (Sarin *et al* 1989) we had reported the major ion chemistry of the Ganga-Brahmaputra river system and the elemental fluxes to the Bay of Bengal through these rivers. Our results showed that the Ganga-Brahmaputra account for ~3% of the total dissolved salts discharged into the world oceans via rivers, similar in magnitude to their contribution to the global water discharge. The chemical denudation rate (the amount of dissolved materials transported per unit drainage area per year) in the drainage basins of these rivers is 2–3 times higher than the global average (Sarin *et al* 1989). The enhanced chemical denudation rate is attributed to high relief and high rainfall in the Himalaya. In this work we focus on the major ion chemistry of the Ganga source waters in the high altitude Himalaya (the Bhagirathi, the Alaknanda and their tributaries), with a view to assessing their role in weathering of the Himalaya and their relative contribution to the higher chemical denudation rate derived for the Ganga. In addition, many of the high altitude streams that we have sampled are away from major industrial and human activities. Hence their water chemistry provides a better assessment of the natural weathering processes occurring in the high altitude Himalaya.

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## 2. Experimental methods

The samples for this study were collected from the Bhagirathi and its tributaries and from the Alaknanda (figure 1). The Bhagirathi and the Alaknanda, after draining the Kumaun Higher and Lesser Himalaya, join at Devprayag to form the Ganga. The geohydrological features of the Kumaun Lesser Himalaya have been described in detail by Sarin *et al* (1989) and Krishnaswami *et al* (1992). The three main lithotectonic units have been recognized in the Kumaun Lesser Himalaya: the autochthonous and allochthonous sediments and the crystalline nappes (Gansser 1964; Valdiya 1980). The autochthonous sediments (Damtha and Tejam groups) mainly consist of greywacks, shales, slates, limestones and dolomites. The carbonates in many regions are associated with pyritic carbonaceous slates. The dominant lithologies of allochthonous sediments (Krol Nappe) are shales, slates, phyllites (which are locally pyritous), conglomerates, carbonates and quartzites. The crystalline nappes are primarily made of schists, micaceous quartzites, calc-silicates, amphibolites, gneisses and granites. The upper



**Figure 1.** Sample location map. Samples 1 to 24 were collected in April 1989 from the Bhagirathi, its tributaries and Alaknanda (table 1). Samples 28 and 29 were collected in October 1990 from the upper reaches of the Alaknanda at Badrinath and Chamoli, respectively.

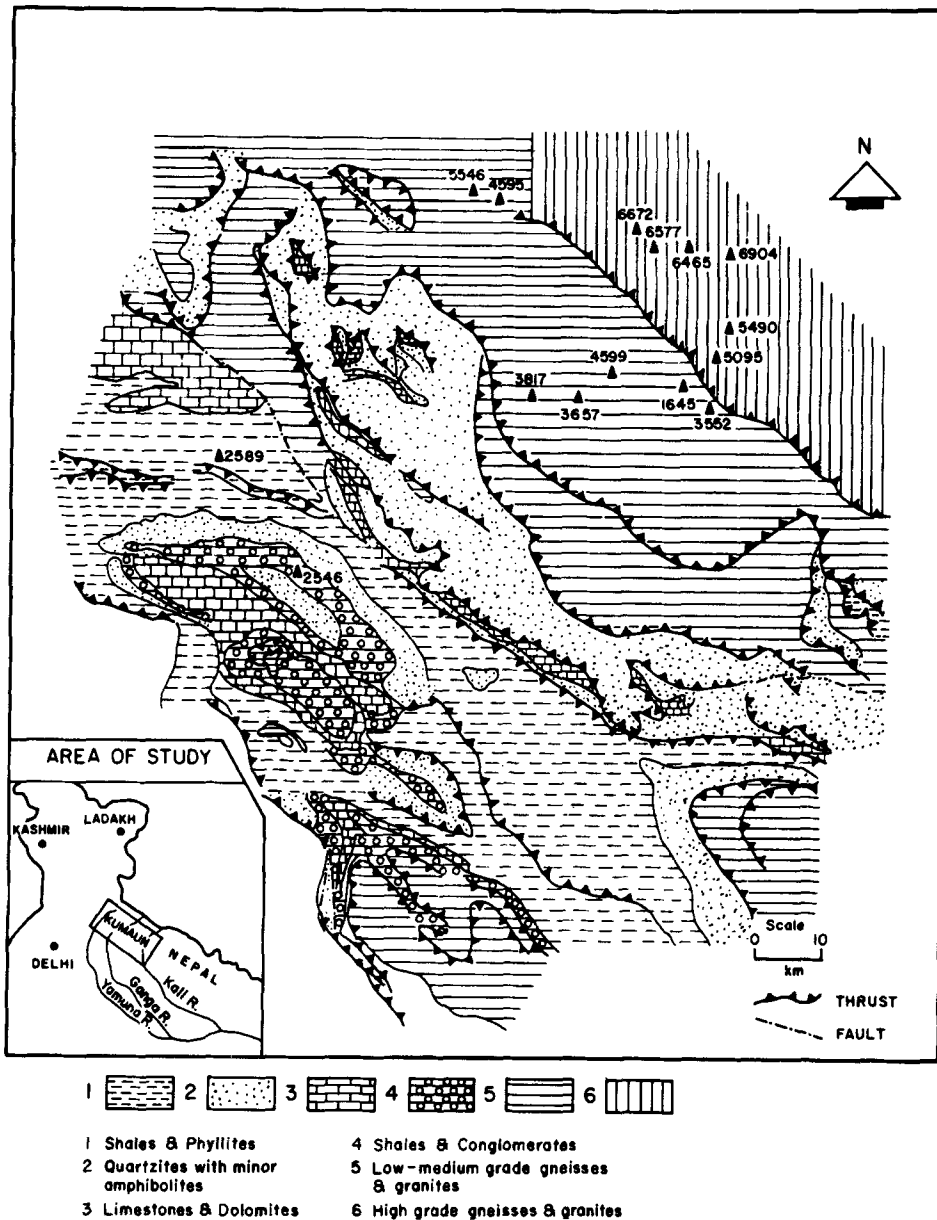


Figure 2. Lithologic map of the drainage basins of the Bhagirathi and Alaknanda rivers in the Kumaun Higher and Lesser Himalaya (from Valdiya 1980).

stream of Bhagirathi and its tributaries (Kedarganga, Son gad, Helgu gad, Pilang gad), the upper Bhilangna and its tributaries (Balganga, Jola gad) and upper Alaknanda, all flow mainly through the crystallines (figure 2). In the crystallines, there are reports of occurrences of shales, slates phyllites and carbonates; in some regions the shales and slates are pyritous. In the downstream regions, the drainage basin of Bhagirathi consists mainly of shales, phyllites and quartzites with minor outcrops of carbonates (figure 2). The Asiganga, the Nagun gad and the Seansu gad, the three

downstream tributaries of the Bhagirathi, flow mainly through sedimentary terrains characterized by slates, phyllites and quartzites. However, the headwaters of the Asiganga lie in the crystallines.

All samples (except two samples from the Alaknanda, #28 and 29) were collected in April 1989 (figure 1). These samples were filtered through 0.4  $\mu\text{m}$  Nuclepore filters within 5–6 hours of collection. The carbonate/bicarbonate ions were measured by acid titration at site. An aliquot of the filtered water was brought to the laboratory for major ion analysis. The anions viz fluoride, chloride, nitrate and sulphate, were measured by ion chromatography. The cations: Na, K, Mg and Ca were measured by atomic spectrophotometry (Sarin et al 1989). The two samples from Alaknanda (#28 and 29) were collected in October 1990, stored unfiltered and later analysed for major ions.

### 3. Results

The major ion composition of the samples analysed is given in table 1. The data reveal that the charge balance between cations and anions is better than  $\pm 5\%$ . Four

**Table 1.** Major ion composition of the Ganga source waters: Bhagirathi, Alaknanda and tributaries.

Sample Code	Stream	Na	K	Mg	Ca	F	Cl	NO <sub>3</sub>	SO <sub>4</sub>	HCO <sub>3</sub>	SiO <sub>2</sub>	TDS (mg/l)
		(μ mol/l)										
13	Bhagirathi	141	64	103	291	62	13	5	364	174	189	79
16	Bhagirathi	131	47	170	392	27	25	12	290	659	127	102
10	Bhagirathi	145	48	139	367	26	27	16	228	660	127	96
11	Bhagirathi	193	51	144	348	28	57	13	199	737	130	99
8	Bhagirathi	150	52	134	373	26	36	8	186	757	132	98
4	Bhagirathi	163	53	149	396	27	43	16	188	853	137	107
5	Bhagirathi	154	51	136	377	25	37	9	170	833	136	102
23	Bhagirathi	154	51	134	385	27	39	15	164	873	139	104
14	Kedarganga	98	83	93	373	36	6	11	460	174	194	91
15	Son gad	55	56	52	367	9	8	7	173	562	113	78
17	Helgu gad	51	29	31	135	28	9	17	29	310	108	39
9	Pilang gad	68	34	52	179	38	11	15	46	427	131	52
12	Asiganga	42	51	60	229	19	9	19	45	543	102	59
7	Nagun gad	249	29	190	555	—	30	—	69	1590	217	151
6	Seansu gad	294	28	139	394	—	55	—	94	1144	254	123
19	Bhilangna	89	46	54	288	26	13	14	120	524	122	69
22	Bhilangna	107	49	67	298	28	18	8	120	601	128	76
3	Bhilangna	115	44	93	310	31	21	9	92	756	142	84
20	Jola gad	184	31	82	160	42	45	—	24	601	197	67
21	Nailchami gad	132	61	187	388	16	56	4	33	1261	195	120
18	Balganga	119	36	108	310	37	27	—	47	853	170	88
28	Alaknanda	44	19	23	175	36	5	—	76	302 <sup>+</sup>	—	35 <sup>+</sup>
29	Alaknanda	70	40	185	422	19	13	—	157	997 <sup>+</sup>	—	101 <sup>+</sup>
24	Alaknanda	107	51	175	429	14	21	16	132	1106	110	115
2	Ganga*	143	51	242	496	18	27	13	210	1241	126	136
1	Song	283	28	432	842	—	36	37	225	2347	412	245

\*Ganga at Rishikesh, figure 1.

<sup>+</sup>In these two samples, HCO<sub>3</sub> is estimated from charge balance and TDS does not include SiO<sub>2</sub>.

of the samples analysed in this study (#2, 3, 23 and 24, figure 1) are collected from the same locations that were sampled by us in 1982–1983 (Sarin *et al* 1989). In our earlier study, the two samples from locations #2 and 23 were collected in March, a time period similar to that sampled in this study. A comparison of the major ion data set for these two samples shows that they agree to within  $\pm 20\%$ .

#### 4. Discussion

##### 4.1 Atmospheric contribution of major ions

The chemistry of river water is largely dominated by the weathering processes in the drainage basin. In addition, atmospheric supply (from marine, terrestrial and anthropogenic sources) of chemical constituents also contributes to the major ion content of rivers. The atmospheric contribution depends on factors such as proximity of the sampling location to the sea coast, vegetation cover and industrial and human activities in the drainage basin. In this study, samples were collected during the months of April–May, a time period during which significant fraction of discharge results from snow/glacier melting in the Himalaya. Therefore, the contribution of major ions via atmospheric deposition to these rivers, particularly those in the upper reaches, can be gauged from the chemistry of snow and surface ice samples collected adjacent to the source regions. Recently, Nijampurkar *et al* (1991) reported major ion composition of snow and surface ice samples (at 4050–4750 m altitude) from the Chhota Shigri Glacier, Central Himalaya. A comparison of the chemistry of snow and surface ice (table 2) with that of the Ganga source water samples (table 1) shows that atmospheric deposition could account for a significant part of the chloride and nitrate in these streams. The atmospheric supply of sodium and potassium can contribute  $\sim 20\%$  to the major ion chemistry whereas that of magnesium, calcium and sulphate can account for only  $\sim 5\%$ .

##### 4.2 Relation between the lithology of the drainage basin and the major ion chemistry

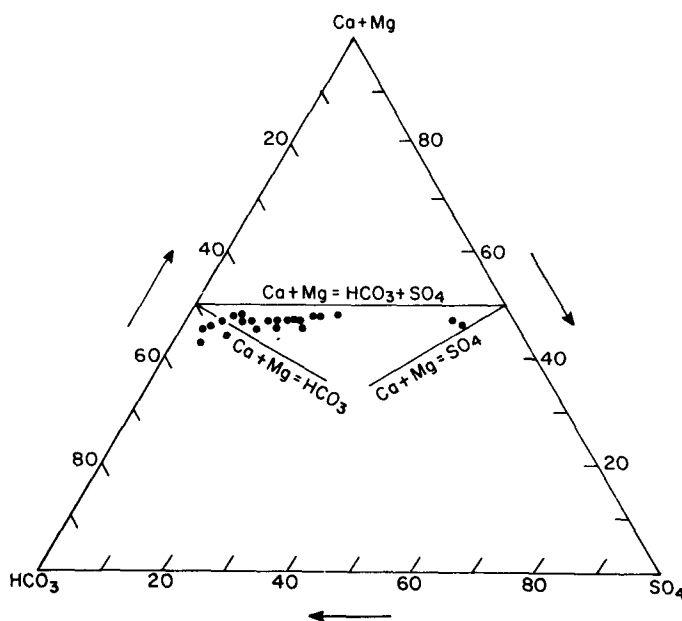
The major ion chemistry of river water provides a means of probing into the weathering reactions in the drainage basin. The nature of the parent rock and the proton source determines the relative concentrations of cations and anions released to solution.

**Table 2.** Average concentrations of major ions in snow, ice and rain waters.

Sample	Na	K	Mg	Ca	Cl	NO <sub>3</sub>	SO <sub>4</sub>
	( $\mu$ mol/l)						
Snow*	17	7	4	6	21	8	2
Ice*	8	3	1.4	2.6	11	7	1.8
Rain water <sup>+</sup>	37	12	16	41	32	—	35

\*Chhota Shigri Glacier, Central Himalaya, (Nijampurkar *et al* 1991)

<sup>+</sup> Foothills of Kumaun Himalaya (Handa 1968)



**Figure 3.** Triangular plot showing the relative abundances of (Ca + Mg),  $\text{SO}_4$  and  $\text{HCO}_3$  (all in units of  $\mu\text{eq/l}$ ). In the samples (#13 and 14) collected from the Bhagirathi and Kedarganga (at Gangotri, figure 1),  $\text{SO}_4$  accounts for as much as 80% of the total anions.

However, different weathering reactions can result in similar water chemistry (Stallard and Edmond 1983, 1987; Sarin *et al* 1989). In addition to the data on water chemistry, information on the lithology of the terrain and mineralogy of suspended phases is generally required to constrain possible weathering reactions.

In these stream waters, calcium and magnesium are the dominant cations. On an average (Ca + Mg), in equivalent units, account for  $\sim 83\%$  (range 64–89%) of the total cations. This observation is quite similar to our earlier results (Sarin *et al* 1989) on the highland rivers of the Ganga-Brahmaputra system (i.e. upper reaches of the Ganga and Yamuna, Ghaghara, Gandak, Brahmaputra and Manas). Among anions, bicarbonate is most abundant in all samples except those of Bhagirathi and the Kedarganga at Gangotri (figure 3, table 1). Bicarbonate accounts for 15–90% of the anions, the range narrows down to 51–90% if the Bhagirathi and Kedarganga samples (at Gangotri) are excluded. In these two samples, sulphate is the principal anion and accounts for  $\sim 80\%$  of the total anions (in equivalent units). In general, the contribution of sulphate to the anion balance is high in the rivers (figure 3) which have part of their drainage in Higher Himalaya, namely the Bhagirathi, Kedarganga, Son gad and Bhilangna. Along the main stream of Bhagirathi, the contribution of sulphate to the total anions decreases from  $\sim 80\%$  near its source (at Gangotri) to  $\sim 20\%$  at Devprayag (table 1). In contrast, the contribution of bicarbonate to the anion balance increases from  $\sim 15\%$  at Gangotri to  $\sim 68\%$  at Devprayag. For the Ganga at Rishikesh, the relative contributions of sulphate and bicarbonate are 24% and 72% respectively, nearly identical to that reported earlier by us based on March 1982 sampling (Sarin *et al* 1989). The sulphate in these river waters is derived either from oxidation of pyrites and/or dissolution of gypsum. Pyritous-carbonaceous slates and

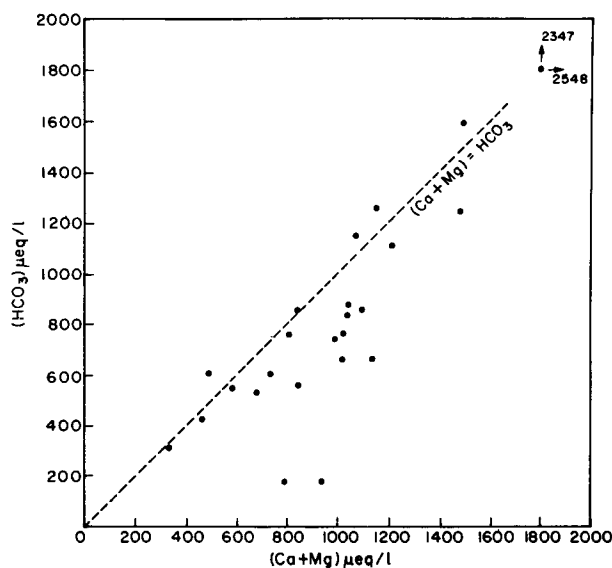
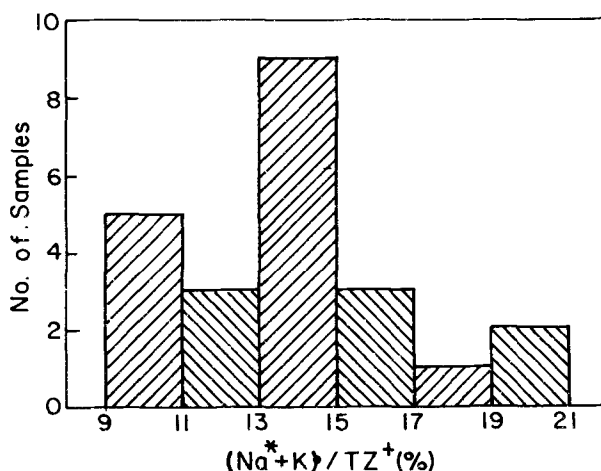


Figure 4. Scatter diagram of  $\text{HCO}_3$  and  $(\text{Ca} + \text{Mg})$ . In most of the samples  $(\text{Ca} + \text{Mg})$  content is in excess over  $\text{HCO}_3$ .

phyllites reported in the various geologic units of the Kumaun Himalaya (Gansser 1964; Valdiya 1980) could be the source of sulphate to these waters.

A plot of  $(\text{Ca} + \text{Mg})$  vs  $\text{HCO}_3$  (figure 4) shows that in most of the samples the  $(\text{Ca} + \text{Mg})$  content is in excess of  $\text{HCO}_3$ , the magnitude of excess being larger for those rivers which have part of their drainage in the Higher Himalaya. The  $(\text{Ca} + \text{Mg}):\text{HCO}_3$  ratio in the Bhagirathi sample at Gangotri is  $\sim 4.5$  and it progressively decreases to 1.2 at Devprayag. A similar decreasing trend is also observed for the Bhilangna, the  $(\text{Ca} + \text{Mg}):\text{HCO}_3$  of 1.3 in the upper reaches (draining through crystallines) and  $\sim 1.0$  at Tehri where it joins the Bhagirathi (table 1, figure 1).

The high contribution of  $(\text{Ca} + \text{Mg})$  to the total cations requires that these rivers weather minerals which are rich in  $(\text{Ca} + \text{Mg})$  such as carbonates and/or alkaline earth silicates. The sodium concentration in these waters is significantly in excess over chloride, the  $(\text{Na}/\text{Cl})$  equivalent ratio is in the range of 3 to 10 suggesting that most of the sodium in these waters results from silicate weathering. On an average,  $(\text{Na}^* + \text{K})$  accounts for about 15% of total cations,  $\text{TZ}^+$  (figure 5), which could largely be derived from silicate weathering ( $\text{Na}^*$  is the sodium content corrected for cyclic contribution using chloride as an index, Stallard and Edmond 1983; Sarin *et al* 1989). Data on the composition of gneisses and granites of the Kumaun Himalaya show that the concentrations of  $(\text{Ca} + \text{Mg})$  in these rocks are similar to or less than that of  $(\text{Na} + \text{K})$  (Valdiya 1980). Therefore, the contributions of  $(\text{Ca} + \text{Mg})$  and  $(\text{Na} + \text{K})$  to these river waters would be similar if the above types of rocks are weathered. Thus,  $(\text{Ca} + \text{Mg} + \text{Na}^* + \text{K})$  resulting from silicate weathering can account for about 30% of total cations in these waters; the remaining  $\sim 70\%$  consisting of  $(\text{Ca} + \text{Mg})$  has to be derived from other sources such as carbonates. The abundance of anions in these waters coupled with the regional lithology show that both carbonic and sulphuric acids provide the protons for the weathering.



**Figure 5.** The  $(\text{Na}^* + \text{K})/\text{TZ}^+$  ratio (expressed as %) is used as an index to assess the contribution of cations via silicate weathering.  $\text{Na}^*$  is the sodium excess over chloride.  $(\text{Na}^* + \text{K})$  and  $\text{TZ}^+$  (total cations) are in equivalent units. On an average  $(\text{Na}^* + \text{K})$  account for  $\sim 13$ – $15\%$  of the total cations.

Our recent study on the strontium isotopic composition of these rivers shows that the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios are in the range of 0.7300 to 0.7986, considerably higher than the global average run-off value of 0.7119 (Trivedi *et al* 1990; Krishnaswami *et al* 1992). The high  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios in these waters require supply of strontium from silicate weathering and rules out the possibility of carbonate weathering as its only source. Krishnaswami *et al* (1992) have suggested that if  $\sim 30\%$  of Sr in the waters is contributed from silicate weathering, it can account for the observed high  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio. These estimates are consistent with those derived above from  $(\text{Na}^* + \text{K})$  content of these waters.

#### 4.3 Chemical denudation rates in the Himalaya

The total dissolved salt (TDS) concentration in these rivers varies nearly over an order of magnitude, from 39 mg/l in Helgu gad (draining through crystallines) to 245 mg/l in the Song (draining through carbonate dominated sediments) (table 1). In general, the rivers which originate in the crystallines have lower TDS content. The concentration of total dissolved salts along the Bhagirathi main stream is remarkably uniform,  $100 \pm 5$  mg/l in all samples except that from Gangotri where TDS content is slightly lower, 79 mg/l (table 1). The chemical denudation rates (CDR) in the Bhagirathi and Alaknanda basins can be determined from their TDS content, drainage area and water discharge (table 3). The data show that the CDR in the Bhagirathi and Alaknanda basin is  $\sim 110$  and  $137$  ton/km<sup>2</sup>/yr, respectively, higher than that observed for the Ganga basin as a whole (Sarin *et al* 1989). The high chemical denudation rate reinforces our earlier conclusion that the high relief and heavy rainfall contributes to intense weathering in the Higher Himalaya.



**Table 3.** Fluxes of total dissolved salts (TDS) and chemical denudation rates (CDR).

River (Location)	Discharge (10 <sup>12</sup> l/yr)	Area (10 <sup>3</sup> km <sup>2</sup> )	TDS conc. (mg/l)	TDS flux (M·ton/yr)	CDR (tons/km <sup>2</sup> /yr)
Bhagirathi* (Devprayag)	8.3 <sup>#</sup>	7.8	104	0.86	110
Alaknanda* (Devprayag)	14.1 <sup>#</sup>	11.8	115	1.6	137
Yamuna <sup>†</sup> (Allahabad)	93	140	222	21	150
Ghaghara <sup>†</sup> (Ayodhya)	94	128	159	15	117
Gandak <sup>†</sup> (Hajipur)	52	46	177	9.2	200

\*Ganga source waters, this study.

<sup>†</sup>Himalayan tributaries of Ganga (Sarin and Krishnaswami 1984).

<sup>#</sup>At Devprayag, estimated from data of Singha and Gupta (1982) and Pal (1986).

## 5. Summary and conclusions

A systematic geochemical study of the Bhagirathi and Alaknanda (Ganga source waters) has been carried out with a view to evaluate their major ion chemistry in terms of the weathering in the high altitude Himalaya. The important conclusions are:

- (i) Calcium, magnesium and bicarbonate are the major ions in most samples suggesting that the chemistry of these high altitude streams is largely dominated by weathering of carbonate rocks. However, in two samples, Bhagirathi and Kedarganga at Gangotri, sulphate is the major anion indicating the importance of pyrite oxidation/gypsum dissolution as a proton source for major ions at this site. Silicate weathering can contribute up to ~ 30% of the total cations (on an equivalent basis). The atmospheric contribution of major ions (except for Cl and NO<sub>3</sub>) to these waters is insignificant relative to the chemical weathering processes in the Himalaya.
- (ii) The TDS content of the Bhagirathi and Alaknanda, at Devprayag, is 104 and 115 mg/l, respectively. The chemical denudation rate in the Bhagirathi and Alaknanda basin is 110 and 137 tons/km<sup>2</sup>/yr, suggesting intense chemical weathering in the Himalaya. These rivers chemically erode their drainage basins at a rate of ~ 0.05 mm/yr.

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