

## Major ion chemistry and weathering control in a high altitude basin: Alaknanda River, Garhwal Himalaya, India

ABHAY KUMAR SINGH & SYED I. HASNAIN

*Himalyan Glacier Project, School of Environmental Sciences, Jawaharlal Nehru University, New Delhi 110067, India*

**Abstract** An analytical study of major cations and anions of the glacier fed Alaknanda River and its tributaries has been carried out to assess the weathering and geochemical processes in the high altitude river basin. The Alaknanda and its tributaries were sampled during pre-monsoon (June 1992) and post-monsoon (October 1992) season for the present hydrogeochemical study. Calcium and magnesium are the major cations, accounting for 85% of the total cations. Among the anions, bicarbonate is the most dominant (78%) with minor contribution from sulphate (19%) and chloride (3%). The average  $(Ca+Mg)/HCO_3$  equivalent ratio of 1.2, a relatively high contribution of  $(Ca+Mg)$  to the total cations ( $TZ^+$ ) and high  $(Ca+Mg)/(Na+K)$  ratio indicate that the carbonate weathering could be the primary source of the major ions to these waters. Wide seasonal and spatial variations are observed in the total dissolved solids (TDS) and total suspended matter (TSM) concentration in the Alaknanda river basin. The chemical denudation rate of Alaknanda is  $133 \text{ t km}^{-2} \text{ year}^{-1}$ , nearly double that of the Ganga river basin and three times the world average. The sediment erosion rate of the basin is  $356 \text{ t km}^{-2} \text{ year}^{-1}$ , double that of the world physical denudation rate. The high rates of denudation are attributed to high relief, intense monsoon rainfall, landslides and glacial erosion in the Himalaya.

### Chimie des éléments majeurs et érosion dans un bassin de haute montagne (Alaknanda, Garhwal Himalaya, Inde)

**Résumé** Une étude des cations et anions majeurs de la rivière Alaknanda d'origine glaciaire et de ses affluents a été entreprise en vue d'évaluer les processus d'érosion physique et chimique dans un bassin de haute montagne. Pour cette étude hydro-géochimique, la rivière Alaknanda et ses affluents ont été échantillonnés avant (juin 1992) et après (octobre 1992) la mousson. Les principaux cations sont le calcium et le magnésium qui représentent 85% du total des cations. En ce qui concerne les anions, on note principalement la présence des bicarbonates (78%) et accessoirement des sulfates (19%) et des chlorures (3%). Un rapport moyen  $(Ca+Mg)/HCO_3$  égal à 1.2, une contribution relativement élevée de la somme  $(Ca+Mg)$  au total des cations ( $TZ^+$ ) et un rapport  $(Ca+Mg)/(Na+K)$  important indiquent que l'érosion des carbonates pourrait être à l'origine des ions majeurs de ces eaux. On observe d'importantes variations saisonnières et spatiales des matières dissoutes totales et des matières en suspension dans le bassin de la rivière Alaknanda. L'érosion chimique de ce bassin est de l'ordre de  $133 \text{ t km}^{-2} \text{ an}^{-1}$ , soit près du double de celle du bassin du Gange et du triple de la moyenne mondiale. L'érosion mécanique est de  $356 \text{ t km}^{-2} \text{ an}^{-1}$ , le double de la moyenne mondiale. Ces valeurs très élevées doivent être attribuées à l'altitude, à l'intensité de la mousson, aux glissements de terrains et à l'érosion glaciaire de l'Himalaya.

## INTRODUCTION

The Himalayas are the largest storehouse of snow and ice outside the polar region and are commonly referred to as "the abode of eternal snow" (Vohra, 1993). The

Himalaya is the main source of water for the rivers in the Indo-Gangetic plains, and all the major river systems of north India, the Ganga, Brahmaputra and Indus, originate from the Himalayan snow and ice fields. It has been observed that the discharge of Himalayan rivers per unit area is roughly twice that of the peninsular rivers. This is mainly due to the perennial contributions from melting of snow and ice. There are 22 glacial fed river systems in India, covering a mountain catchment of over  $10 \times 10^6$  km<sup>2</sup> (Bahadur, 1988). The degree of glaciated area varies in these river systems from 3.4% for the Indus, 3.2% for the Ganga and 1.3% for the Brahmaputra.

Highland proglacial streams are very active agents of erosion and transportation. The Himalayan rivers Ganga and Brahmaputra together account for 3% of the total global flux of dissolved load to the world's oceans (Sarin *et al.*, 1989). It has been estimated that the non-Himalayan rivers of peninsular India carry less than 5% of the total mass transport as compared to Himalayan rivers (Subramanian, 1979). Thus a high altitude Himalayan river basin provides a natural unit within which one can examine natural weathering and geochemical processes. However, even today, the study and management of the Himalayan river basins is unfortunately constrained by a lack of reliable hydrological data. Although some work has been done in the last few decades (Hasnain *et al.*, 1989; Hasnain, 1992, 1996; Hasnain & Renoj 1996; Chauhan & Hasnain 1993; Sarin *et al.*, 1992), it is either confined to a near source region or is based on only few samples. Adequate understanding of the Himalayan proglacial streams is extremely important for the development of a realistic programme for utilizing the potential of water that exists in the form of snow and ice in this area. Several studies have been carried out in the lower part of the Ganges river system (Abbas & Subramanian, 1984; Sarin *et al.*, 1989; Handa, 1972), but very little information is available on geochemical aspects of the Ganga headwaters. The present work is aimed towards developing baseline data for river water quality of the Alaknanda River, a major tributary of the Ganga River, and to understanding the weathering and geochemical processes active in high altitude river basins.

## ALAKNANDA BASIN

The Alaknanda river basin,  $11.8 \times 10^3$  km<sup>2</sup>, is formed by the proglacial Alaknanda stream and its tributaries (Fig. 1), which are mostly fed by snow, ice melt and monsoon precipitation. The sources of the Alaknanda mainstream are the twin glaciers, Satopanth and Bhagirath Kharak (elevation 3800 m), 13 km north of the temple town of Badrinath. The Alaknanda is joined on the left bank by the Saraswati, Dhauliganga, Garunganga, Patalganga, Birehiganga, Nandakini and Pindar streams and on the right bank by the Mandakini. After Karanprayag, the Alaknanda turns to the southwest and flows past Srinagar and joins the second major Himalayan stream the Bhagirathi (draining from Gangotri Glacier) at Devprayag to form the River Ganga.

The higher reaches of the Alaknanda basin are characterized by active glaciation. Glaciers, cirque basins, glacial lakes, U-shaped valleys, moraines and

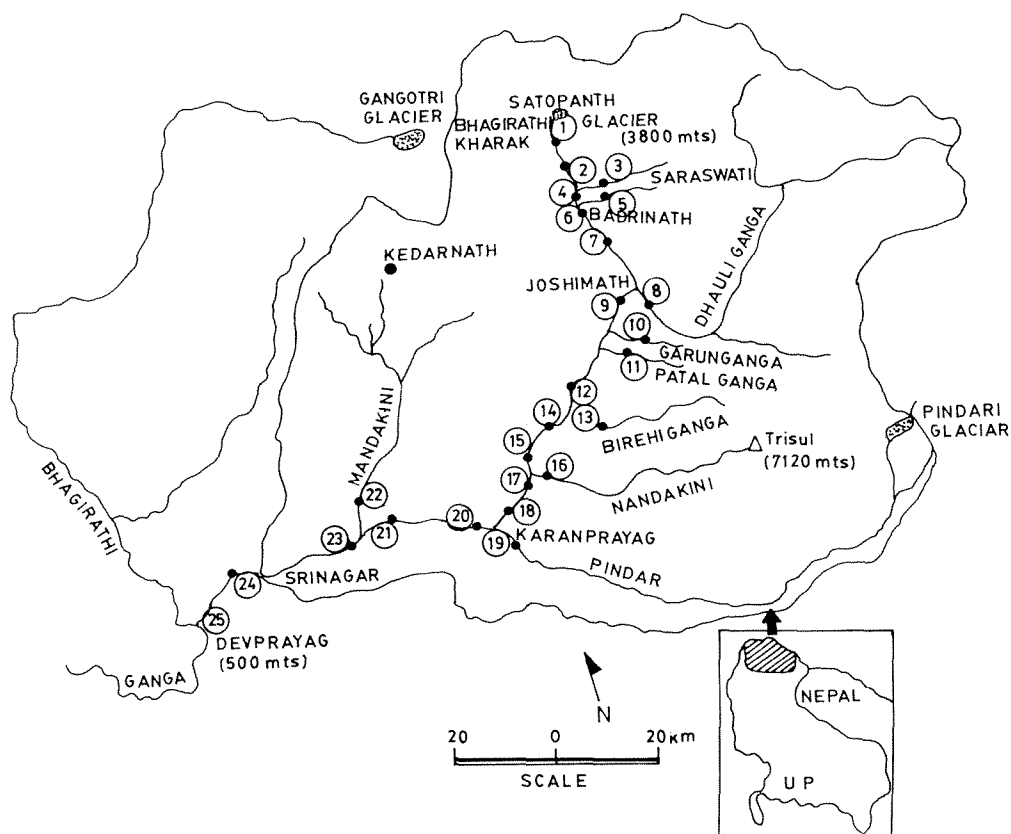


Fig. 1 Drainage map of the Alaknanda basin, showing sampling sites.

avalanche slopes are the common landforms in the region (Sah, 1991). The river flows for a distance of 240 km from its source (3800 m a.m.s.l.) to Devprayag (500 m a.m.s.l.). The river in its upper course flows through narrow and deep gorges and then enters its lower course at an elevation of 900 m, 25 km downstream of Joshimath. The annual rainfall in the basin ranges from 1000 to 1600 mm, and 75% of the rainfall occurs during the monsoonal months July–September (Dasgupta, 1975).

The discharge of the Alaknanda at the confluence in Devprayag is greater than that of the Bhagirathi. The maximum and minimum discharge values for the river Ganga at Devprayag during the period 1990–1991 were 4061 and 125  $\text{m}^3 \text{s}^{-1}$  respectively (Central Water Commission, 1991). During this period, the maximum and minimum contribution of the Alaknanda to the total discharge was 3000 and 85  $\text{m}^3 \text{s}^{-1}$  respectively; thus in the Himalayan basin of the Ganga, the Alaknanda is twice as big as its counterpart, the Bhagirathi. The Alaknanda river basin, like other Himalayan basins, experiences a strongly seasonal climate, which is reflected in the monthly variations in the streamflows. Maximum flow takes place during June–September, when both rainfall and rate of snowmelt are at maximum levels.

The Himalayan rivers carry 69–83% of their annual flow during the summer monsoon months (Bruijnzeel & Bremmer, 1989).

**GEOLOGY OF THE BASIN**

The Alaknanda River catchment is underlain by both sedimentary and highly metamorphosed gneissic rocks (Gansser, 1964; Valdiya, 1980). In its upper course, the Alaknanda flows through the Central Crystalline zone, which is composed of migmatized and granitized Archean metasediments (Fig. 2). After passing the Central Crystalline, the river traverses through limestones, marbles and quartzitic sequences of the Tejam and Berinag Formations. Before its confluence with the Bhagirathi, the stream passes through the limestone and dolomite-bearing Uttarkashi Formation and the outcrops of phyllite and micaceous graywackes of the Chandpur Formation. The tributaries of the Alaknanda also flow through a varied terrain of quartzites, limestones, shales and slates.

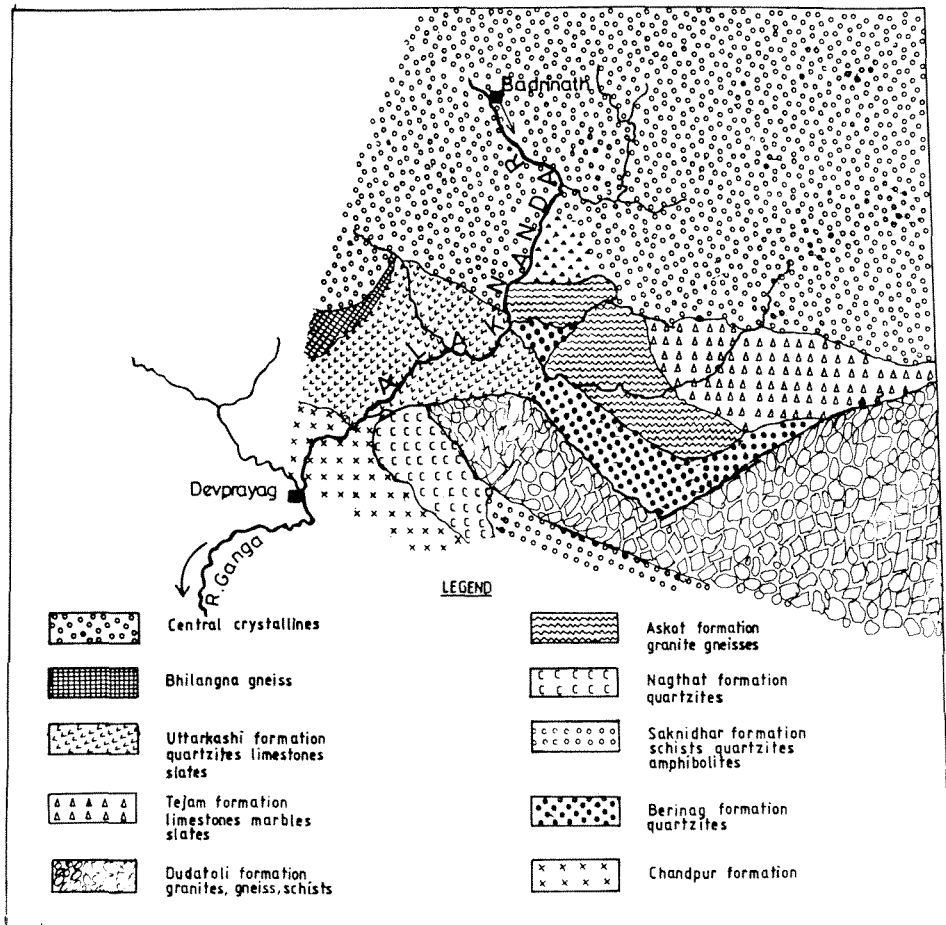


Fig. 2 Geological map of the Alaknanda basin.

## MATERIALS AND METHODS

The Alaknanda and its tributaries were sampled during the pre-monsoon (June 1992) and post-monsoon (October 1992) seasons for the present geochemical study. One litre water samples were collected in polyethylene bottles from various parts of the river basin (Fig. 1). Electrical conductivity (EC) and pH values were measured in the field using a portable conductivity and pH meter. The water samples were filtered through 0.45  $\mu\text{m}$  Millipore membrane filters within a week and sediment collected on the filter paper was weighed after drying for determination of total suspended matter (TSM). In the laboratory, major cations (Ca, Mg, Na, and K) were determined by atomic absorption spectrophotometer (GBC 906) after calibrating the instrument with salt standards. The cations Ca and Mg were analysed in the absorbance mode and Na and K in the emission mode. The molybdosilicate method and turbidimetric method (APHA, 1985) were used to measure the concentrations of dissolved silica and sulphate respectively. The mercury thiocyanate method (Florence & Farrar, 1971) was used for determination of chloride, and bicarbonate was determined by acid titration (APHA, 1985).

Three replicates were run for cation analysis and the instrument was recalibrated after every 15 samples. An overall precision, expressed as percent relative standard deviation (RSD) was obtained for the entire samples. Analytical precision for Ca, Mg, Na, and K were 2.0, 1.5, 2.5 and 1.2 RSD, respectively. Overall data reproducibility for anions was within  $\pm 5\%$ .

## RESULTS AND DISCUSSION

### Major ion chemistry

The chemical composition of the Alaknanda river water and its tributaries for the pre-monsoon and post-monsoon seasons is shown in Table 1. The table also shows electrical conductivity (EC) and the ratio of TDS/EC. The charge balance (calculated by the formula:  $\text{TZ}^+ - \text{TZ}^- / \text{TZ}^+ + \text{TZ}^- \times 100$ ) between cations and anions ( $< 10\%$ ) and ratio of TDS/EC (0.8) are within acceptable limits, confirming the reliability of the analytical results. Total cations and anions are related by the equation,  $\text{TZ}^+ = 0.89\text{TZ}^- \pm 7.06$  with a correlation coefficient of 0.97 for 50 samples.

The Alaknanda river water is neutral to mildly alkaline. The pH for the Alaknanda water ranges between 7.07 and 8.46. The electrical conductivity (EC) of the Alaknanda water ranges between 25 and 240  $\mu\text{S cm}^{-1}$  (average 114  $\mu\text{S cm}^{-1}$ ). The major anions constitute more than 70% of the total dissolved solids (TDS). Bicarbonate is the most dominant ion in the Alaknanda river water followed by Ca,  $\text{SO}_4$ , Mg,  $\text{H}_4\text{SiO}_4$ , K, Na and Cl. The average bicarbonate concentration accounts for about 56% of the TDS and in microequivalent units it constitutes about 78% of the total anions. The bicarbonate concentration in Alaknanda basin water ranges from 111–2438  $\mu\text{eq l}^{-1}$  in the pre-monsoon season to 230–2617  $\mu\text{eq l}^{-1}$  in the post-monsoon

Table 1 Chemical and sediment load characteristics of Alaknanda river basin water.

Sampling sites	EC	pH	Ca	Mg	Na	K	HCO <sub>3</sub>	SO <sub>4</sub>	Cl	H <sub>4</sub> SiO <sub>4</sub>	TDS	TDS/EC	TSM
1	a b	7.30 7.42	177 255	43 60	42 53	42 45	221 270	40 88	8 7	33 45	26 34	0.66 0.7	2163 5
2	a b	7.08 7.12	161 237	40 53	39 50	34 42	166 232	53 87	13 8	34 46	22 31	0.6 0.67	1416 7
3	a b	7.07 7.50	147 239	23 50	30 49	18 34	111 248	45 105	51 5	21 43	17 32	0.69 0.67	834 6
4	a b	7.10 7.47	166 242	36 43	49 55	41 40	162 230	57 118	29 15	30 43	23 33	0.60 0.72	525 6
5	a b	7.12 7.93	187 374	53 87	42 45	32 48	182 377	55 158	28 5	21 36	23 46	0.36 0.50	519 5
6	a b	7.12 7.58	198 305	27 51	48 60	28 37	190 287	57 127	17 15	28 43	24 38	0.70 0.78	642 10
7	a b	7.24 7.72	259 387	43 62	50 96	39 41	261 375	67 162	16 15	28 46	31 48	0.76 0.79	2242 9
8	a b	7.67 8.23	511 007	96 186	55 180	48 66	582 888	290 398	27 24	27 47	67 108	0.60 0.68	346 14
9	a b	7.43 7.77	274 372	47 53	63 114	48 50	284 364	61 122	18 12	26 44	33 45	0.77 0.84	511 8
10	a b	8.01 8.34	509 793	190 463	41 82	58 62	438 482	305 391	18 14	52 75	217 236	1.20 1.00	4 3
11	a b	8.02 8.36	397 718	042 601	66 92	58 184	836 617	304 375	28 16	50 72	177 248	1.00 1.03	8 3
12	a b	7.57 8.31	322 870	327 527	153 112	57 70	885 089	164 294	23 20	29 47	163 115	1.14 0.84	540 19
13	a b	8.06 8.26	116 856	253 462	102 136	51 61	325 935	159 299	24 19	30 40	122 104	0.87 0.84	537 17

Table 1 continued.

Sampling sites	EC	pH	Ca	Mg	Na	K	HCO <sub>3</sub>	SO <sub>4</sub>	Cl	H <sub>4</sub> SiO <sub>4</sub>	TDS	TDS/EC	TSM
14	a 175	7.69	048	574	86	74	243	202	25	39	123	0.70	65
	b 196	8.46	349	627	127	91	949	270	21	54	179	0.91	3
15	a 148	7.50	117	326	104	63	349	161	13	30	125	0.84	619
	b 131	8.22	898	474	130	76	260	278	14	51	125	0.96	20
16	a 99	7.78	826	313	85	62	977	438	21	34	109	1.11	60
	b 135	8.23	253	449	101	74	284	524	16	70	147	1.09	5
17	a 140	7.80	124	329	90	73	256	201	19	31	121	0.87	642
	b 130	8.25	926	476	117	77	047	328	15	54	115	0.89	14
18	a 159	8.05	177	333	62	58	293	134	35	29	121	0.76	720
	b 129	8.26	886	490	102	69	066	238	15	53	111	0.86	15
19	a 134	7.42	895	319	62	70	035	113	18	23	97	0.73	210
	b 143	8.36	135	554	85	65	455	114	15	57	134	0.94	5
20	a 148	7.80	987	326	66	64	107	94	18	31	103	0.70	293
	b 137	8.27	938	486	115	67	148	205	12	53	115	0.84	10
21	a 167	7.98	243	336	79	69	350	151	18	30	127	0.76	758
	b 135	8.21	021	438	111	69	177	199	19	53	118	0.87	12
22	a 52	7.12	374	66	78	40	361	76	29	39	42	0.81	56
	b 81	7.99	571	163	98	68	658	103	17	78	71	0.88	5
23	a 160	7.94	210	312	78	67	250	140	13	37	119	0.75	1297
	b 122	8.22	921	417	110	77	075	200	24	60	111	0.91	11
24	a 151	7.72	080	315	74	64	164	154	36	40	113	0.75	514
	b 126	8.21	903	443	114	66	134	205	19	60	114	0.91	9
25	a 150	8.20	092	328	101	81	150	159	35	38	114	0.76	585
	b 124	8.20	918	435	105	65	089	188	18	58	110	0.89	12

Units:  $\mu\text{eq l}^{-1}$ , except EC ( $\mu\text{S cm}^{-1}$ ), H<sub>4</sub>SiO<sub>4</sub> ( $\mu\text{mol l}^{-1}$ ) and TDS and TSM ( $\text{mg l}^{-1}$ ).

a = pre-monsoon (June 1992);

b = post-monsoon (October 1992).

season, with an average value of  $958 \mu\text{eq l}^{-1}$ . The other anions, such as  $\text{SO}_4$  and  $\text{Cl}$ , have minor contributions to the total anions. The sulphate concentration in the Alaknanda ranges between  $40\text{--}524 \mu\text{eq l}^{-1}$  (average  $185 \mu\text{eq l}^{-1}$ ) and it contributes 20% of the total anions. Chloride concentrations in the Alaknanda basin are very low, ranging between  $5\text{--}51 \mu\text{eq l}^{-1}$  and account for 3% of the total anions. The water from the Alaknanda River is found to contain  $21\text{--}78 \mu\text{mole l}^{-1}$  of dissolved silica with an average value of  $43 \mu\text{mole l}^{-1}$ .

The major cations constitute nearly 26% of the total dissolved solids (TDS). Among the cations, calcium is the major constituent, ranging between  $147\text{--}1509 \mu\text{eq l}^{-1}$  in the pre-monsoon season and  $237\text{--}1793 \mu\text{eq l}^{-1}$  in the post-monsoon season with an average of  $799 \mu\text{eq l}^{-1}$ . It accounts for 64% of the total cations in equivalent units. Magnesium is second in cationic abundance, accounting for 21% ( $23\text{--}1601 \mu\text{eq l}^{-1}$ ) of the total cations. Sodium ( $84 \mu\text{eq l}^{-1}$ ) and potassium ( $60 \mu\text{eq l}^{-1}$ ) are less predominant ions in the Alaknanda basin and together they account for only 15% of the total cations.

Table 2 summarizes the chemical composition of some of the selected Garhwal and Kumaun Himalayan streams. The TDS content of the Alaknanda is higher than the Bhagirathi, Sarju and Gomti. It is comparable to the Ramganga but lower than the spring-fed Kumaun Himalayan stream Gaula. Such differences in the chemical composition are a net function of natural rock weathering, atmospheric contribution and anthropogenic activities in the drainage basin.

### Source of dissolved ions in Alaknanda river water

The weathering of rock forming minerals, with minor contributions from cyclic sea salt and pollution, is the major source of ions in river water (Berner & Berner, 1987). Thus the chemical composition in terms of dissolved major ions can be explained on the basis of weathering of various rocks of the drainage basin. The chemical composition of glacial meltwater demonstrates that chemical weathering takes place beneath the glacier (Reynold & Johnson, 1972; Raiswell, 1984) and glaciated catchments undergo more intense weathering than catchment which do not have a glacier (Reynold & Johnson, 1972; Collins, 1979). The two major anions  $\text{HCO}_3$  and  $\text{SO}_4$  in surface water are mainly derived from the dissolution of atmospheric  $\text{CO}_2$  in water and the oxidation of sulphides (Garrels & Mackenzie, 1971). These two reactions provide the bulk of the protons which chemically weather carbonates, silicates and aluminosilicates in the drainage basin.

The dissolution of carbonate rocks proceeds more rapidly than silicate breakdown and is the likely mechanism of solute acquisition. The quantification of solution products of silicate weathering is difficult because of the incongruent dissolution (Sarin *et al.*, 1989). The relative proportions of the various ions in solution depend on their relative abundance in the host rock and on their solubility. Sources of dissolved ions in the Alaknanda river basin can be evaluated by looking at associations among ions. A parametric correlation analysis for average values of all



Table 2 Chemical composition of the Alaknanda and other selected Himalayan streams.

River/stream	pH	EC	Ca	Mg	Na	K	HCO <sub>3</sub>	SO <sub>4</sub>	Cl	Silica	TDS
Alaknanda <sup>a</sup> at Devpryag	8.2	37.2	20.2	4.9	2.36	2.85	68.3	8.3	0.92	4.6	112
Alaknanda <sup>a</sup> (average) <i>n</i> = 50	7.8	13.6	16.1	4.1	1.91	2.33	58.1	8.9	0.67	4.1	96
Bhagirathi <sup>b</sup> at Devpryag	8.0	10.3	14.1	3.6	2.92	3.21	42.1	16.2	1.4	5.2	89
Bhagirathi <sup>b</sup> (average) <i>n</i> = 26	7.7	02.1	11.7	3.3	2.83	3.41	38.9	20.3	0.82	5.2	81.5
Guala <sup>c</sup> at Ramibagh	-	-	26.5	8.6	5.9	2.5	132.7	29.0	2.1	5.1	212.8
Ramganga <sup>d</sup>	7.9	83.5	25.3	12.9	3.7	1.6	105.8	4.3	8.4	-	97.4
Sarju <sup>d</sup>	7.7	40.7	19.7	12.4	4.2	2.0	98.1	2.5	8.5	-	87.7
Gomti <sup>d</sup>	7.4	78.9	11.4	6.6	4.8	2.2	54.9	1.3	9.2	-	40.7
Ganga <sup>e</sup> at Rishikesh	-	-	15.9	5.7	3.32	1.57	61.2	15.5	1.47	9.1	114.0
Yamuna <sup>e</sup> at Yamunagar	-	-	23.6	7.9	4.65	1.77	102.3	24.0	1.8	10.0	176.0

Units: mg l<sup>-1</sup> except EC ( $\mu\text{S cm}^{-1}$ ) and pH.a = present study; b = Pandey (1993); c = Bartarya (1993); d = Pandey *et al.* (1991); and e = Sarin *et al.* (1983).

**Table 3** Correlation matrix\* of the dissolved ions in the Alaknanda water.

	EC	pH	Ca	Mg	Na	K	HCO <sub>3</sub>	SO <sub>4</sub>	Cl	H <sub>4</sub> SiO <sub>4</sub>	TDS
EC	1.00										
pH	0.92	1.00									
Ca	0.98	0.92	1.00								
Mg	0.86	0.70	0.88	1.00							
Na	0.56	0.70	0.57	0.22	1.00						
K	0.84	0.79	0.84	0.76	0.54	1.00					
HCO <sub>3</sub>	0.95	0.84	0.98	0.95	0.46	0.81	1.00				
SO <sub>4</sub>	0.70	0.68	0.73	0.64	0.50	0.61	0.68	1.00			
Cl	0.26	0.35	0.25	0.12	0.31	0.21	0.17	0.22	1.00		
H <sub>4</sub> SiO <sub>4</sub>	0.58	0.49	0.65	0.73	0.16	0.62	0.68	0.51	0.15	1.00	
TDS	0.96	0.86	0.98	0.94	0.49	0.82	1.00	0.74	0.20	0.70	1.00

\* Average data of two sampling seasons (June and October) used for correlation calculation.

measured parameters is given in Table 3. HCO<sub>3</sub> is better correlated with the base cations Ca ( $r^2 = 0.98$ ), Mg ( $r^2 = 0.95$ ) and K ( $r^2 = 0.81$ ).

The higher concentration of HCO<sub>3</sub> in Alaknanda river water and its positive correlation with Ca and Mg indicates their common source, from the dissolution of carbonates. The stoichiometry of carbonate weathering reactions demands that carbonate-derived calcium and magnesium [(Ca+Mg)<sub>C</sub>] should be equal to the carbonate-derived bicarbonate [(HCO<sub>3</sub>)<sub>C</sub>]. The analysis shows that in the Alaknanda basin, total calcium and magnesium [(Ca+Mg)<sub>T</sub>] is not very different from the total bicarbonate [(HCO<sub>3</sub>)<sub>T</sub>]. A plot of (Ca+Mg) vs HCO<sub>3</sub> (Fig. 3(a)) shows that in most of the samples the (Ca+Mg) content is slightly in excess of HCO<sub>3</sub>, the magnitude of excess being larger for most of the tributaries, suggesting that excess of (Ca+Mg) in these waters should be balanced by SO<sub>4</sub> and Cl. The estimation of the carbonate and silicate fractions of HCO<sub>3</sub> by using the Raymahasay (1986) method, indicates that in the Alaknanda basin 78% of bicarbonate comes from carbonate weathering and 22% from silicate weathering. The ratio of carbonate and silicate fraction of bicarbonate [(HCO<sub>3</sub>)<sub>C</sub>]/[(HCO<sub>3</sub>)<sub>Si</sub>] is high (2–8) at all sampling stations particularly in the tributaries, reflecting the dominance of carbonate weathering over silicate weathering. The (Ca+Mg) vs TZ<sup>+</sup> plot (Fig. 3(b)) shows that most of the points approach equiline i.e. 1:1 trend with an average equivalent ratio of 1.12. The relatively high contribution of (Ca+Mg) to the total cations (TZ<sup>+</sup>), the high (Ca+Mg)/(Na+K) ratio (8), and the low (Na+K)/TZ<sup>+</sup> ratio (0.15) indicate that carbonate weathering is the major source of solutes in these waters. The geology of the area also supports this conclusion.

The analytical results show that there is little variation in sodium and potassium concentrations throughout the basin. Sodium is a major component of sea water. The present study area is at high altitude and far away from the sea, so the cyclic contribution of the sodium is not of much importance for the Alaknanda basin. Further, the sodium concentration in these waters is significantly in excess of the chloride concentration; the average Na:Cl equivalent ratio is high (5:1), suggesting that much of the Na and K in the water has a source other than precipitation and could be derived from silicate weathering (Stallard & Edmond, 1983).

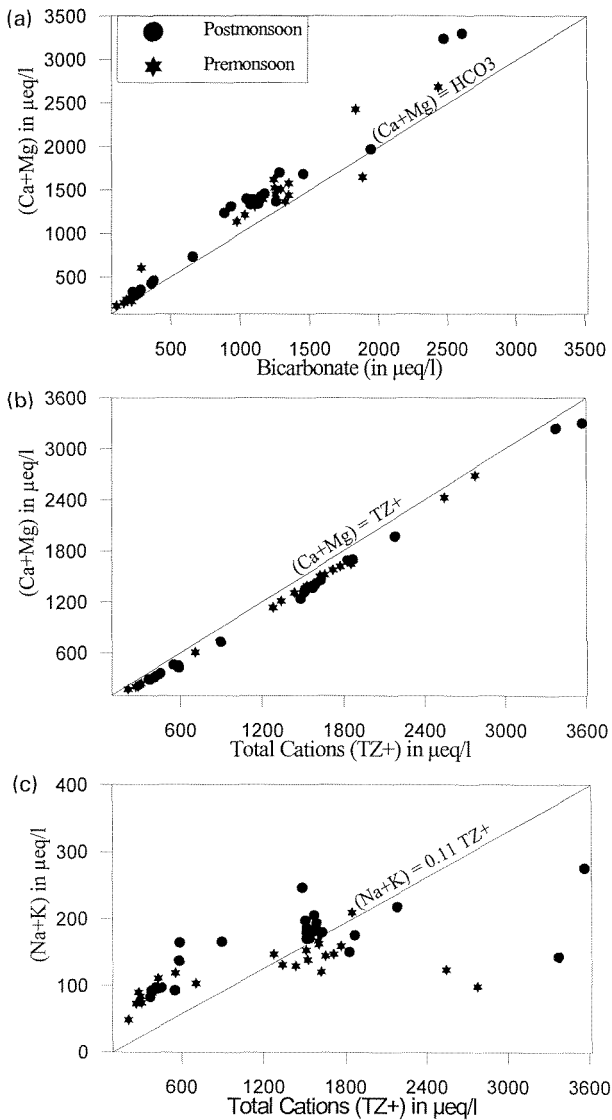
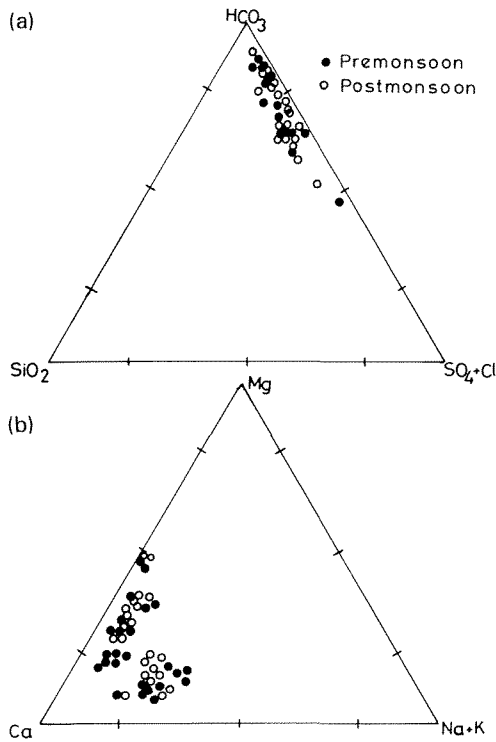


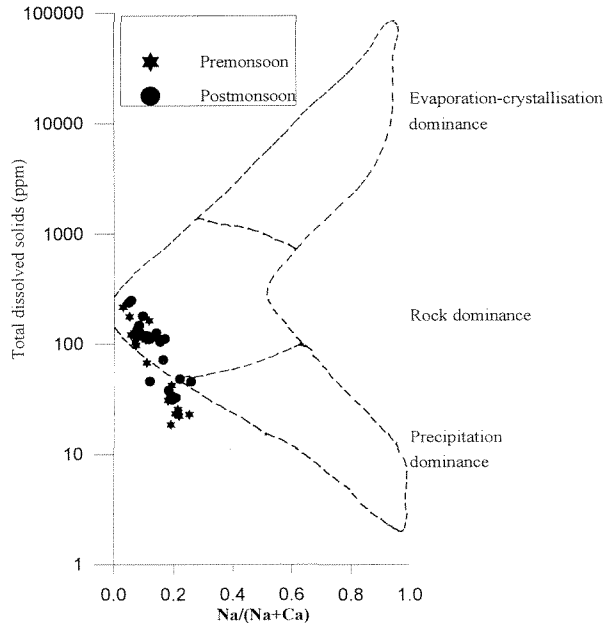
Fig. 3 Scatter diagram between (a)  $(Ca+Mg)$  vs bicarbonate; (b)  $(Ca+Mg)$  vs total cations ( $TZ^+$ ); and (c)  $(Na+K)$  vs total cations ( $TZ^+$ ).

On a ternary anion diagram (Fig. 4(a)) relating  $HCO_3$ ,  $(H_4SiO_4)$  and  $(SO_4+Cl)$ , most of the data cluster towards the alkalinity apex with secondary trends towards  $(SO_4+Cl)$ . A similar cation diagram relating  $Ca$ ,  $Mg$  and  $(Na+K)$  shows that most of the data fall on the left corner of the triangle with a trend from the  $Ca$  apex towards the centre of the field (Fig. 4(b)). Taken together, these arrays also indicate the dominance of carbonate weathering in the present drainage basin.

The variation of weight ratio  $Na/(Na+Ca)$  as a function of total dissolved solids (TDS) has been plotted to decipher the mechanism controlling water chemistry



**Fig. 4** (a) The ternary anion diagram showing the relationship between  $\text{SiO}_2$  ( $\mu\text{mole l}^{-1}$ ),  $(\text{SO}_4+\text{Cl})$  and  $\text{HCO}_3$  ( $\mu\text{eq l}^{-1}$ ); and (b) the ternary cation diagram showing the relationship between  $(\text{Na}+\text{K})$ ,  $\text{Ca}$ , and  $\text{Mg}$  ( $\mu\text{eq l}^{-1}$ ).



**Fig. 5** Variation of the weight ratio of  $\text{Na}/(\text{Na}+\text{Ca})$  as a function of TDS (after Gibbs, 1970).

(Gibbs, 1970). This plot (Fig. 5) places the Alaknanda River in the region of rock dominance, which is consistent with the observation that the dissolution of various rock forming minerals in water is a primary factor controlling the chemistry of water in the Alaknanda River. However, some samples fall outside the boomerang region that encompasses most water of the earth's surface. These samples were collected near the snout of the glacier and reflect the low TDS of the glacier meltwater. Thus the Gibbs assumption that at low to moderate levels of TDS, sodium is primarily supplied by precipitation may not be valid, particularly in the glacial environment, since they can be a significant weathering product of silicate rocks in certain circumstances.

The value of partial pressure,  $P_{CO_2}$  for Alaknanda water is slightly higher ( $10^{-3.0}$ ) than the atmospheric level ( $10^{-3.5}$ ) and an open system weathering is indicated (Fig. 6(a)). The slightly higher  $P_{CO_2}$  of the river water is a global trend indicating that rivers are commonly out of equilibrium with the atmosphere (Garrels & Mackenzie, 1971). The possible explanation for the slightly higher values of  $P_{CO_2}$  could be (a) that the river channel is supplied with groundwater high in  $CO_2$  and/or (b) the relatively higher rate of solubility in comparison to release of excess of  $CO_2$

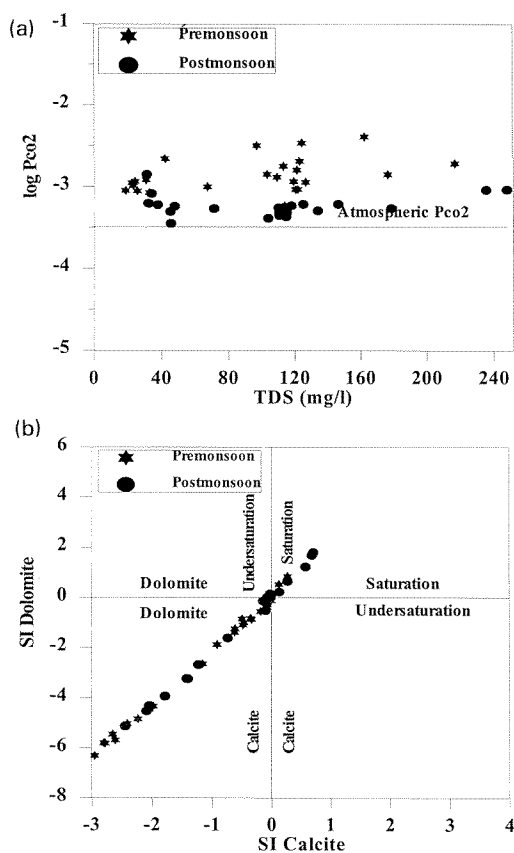


Fig. 6 (a) Relationship between  $\log P_{CO_2}$  and TDS; and (b) saturation indices for calcite ( $SI_c$ ) and dolomite ( $SI_d$ ) of Alaknanda water.

gas in a turbulent and low temperature environment (Stumm & Morgan, 1970). The plot (Fig. 6(b)) of saturation indices ( $SI$ ) for calcite ( $SI_c$ ) and dolomite ( $SI_d$ ) shows that most of the samples are undersaturated with respect to both calcite and dolomite. However some samples of the lower Alaknanda are supersaturated and carbonate precipitation may occur. Carbonates form secondary mineral phases in the sediments of the region (Singh, 1993).

### Seasonal and spatial variation of the dissolved ions

The seasonal variation of solute concentration in the Alaknanda river basin is given in Table 1, which shows that samples from the upper Alaknanda and its tributaries have high ionic concentrations during low flow regime (October) and low concentrations in the month of June (high flow regime). Such variation in the concentrations of dissolved solids is indicative of a climatic control on the intensity of processes operating in the source area. High incoming solar radiation in June is supplying heat for melting of the glacier surface, resulting in increase in discharge and dilution of the solute concentrations. With a reduced heat supply by October, the melting is also reduced, resulting in an increase of solute concentrations. The negative correlation between solute concentration and discharge near the source area is also reported by Chauhan & Hasnain (1993). The TDS and EC values for the samples of the lower Alaknanda are high during high flow (June), which may be due to intense chemical weathering of the sedimentary formations in the lower reaches of the Alaknanda drainage basin as opposed to the crystalline rocks in the upper drainage basin and/or contribution from groundwater.

The change in streamwater concentration as a function of increasing basin area was evaluated by collecting samples at 16 sites from source to Devprayag. Ionic concentration in stream water generally increases with an increasing basin area (Fig. 7). This downstream increase in ionic concentration is related to the concentrating effects of the tributaries which have higher TDS and to the change in the lithology. There was little change in ionic concentration for the upper stretch between the source and Joshimath. One possible explanation for this is that geochemical and hydrological processes were similar and the lithology along this stretch is dominated by the granitic gneisses of the Central Crystallines. Ionic concentrations then increased gradually with an increase in distance as the river enters the middle and lower reaches, which are predominantly sedimentary rocks. The concentration of calcium and bicarbonate increased from 177 and 221  $\mu\text{eq l}^{-1}$ , respectively, at the source to 1092 and 1150  $\mu\text{eq l}^{-1}$ , respectively, at Devprayag in the pre-monsoon season. The higher concentrations of Ca, Mg and  $\text{HCO}_3$  in the middle and lower reaches of the basin are due to weathering of limestone and dolomites of the Uttarkashi and Tejam formation.

Variation in TDS in the Alaknanda basin is controlled primarily by lithology and climate. The present study indicates that meltwater in the source area contains approximately 27, 31 and 26% of the Ca, TDS, and  $\text{HCO}_3$  respectively of the Alaknanda water (average of 50 samples) and 21, 22 and 27% respectively of the

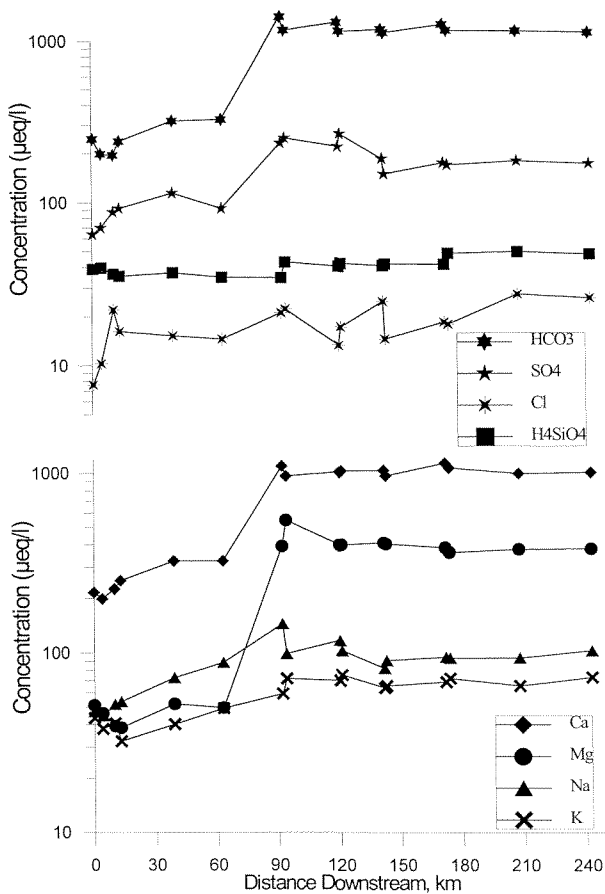


Fig. 7 Downstream variation in average concentration of dissolved ions.

water at Devprayag. The low concentrations at the source region are probably due to lithology, less susceptible to weathering. In the downstream direction lithology prone to chemical erosion, increase in pH and temperature may contribute to the increase in ionic concentrations. The downstream decreasing TSM/TDS ratio, which is very high near the source (85) during the sampling season of June and low downstream (3–4), signifies that physical weathering is more pronounced in the upper reaches of the basin. In the case of Himalayan rivers it has been observed that high altitude favours physical weathering (Subramanian & Dalvi, 1978). In the Alaknanda, extreme altitudes compounded by steep gradients cause more physical weathering than chemical weathering.

### Sediment load

The amount of suspended matter in river water depends on the hydraulic condition of the streams and the availability of suitable size fractions of sediment (Gurnell, 1987).

The Himalayan rivers carry large sediment loads as they drain through the most active tectonic zones and easily erodible foothills of the Himalaya (Subramanian & Dalvi, 1978). Erosion by glaciers and streams, mass movements and human activities all contribute to the suspended load of the Alaknanda stream. Further, the turbulent nature of the flow and the low temperature of the stream also enhance the suspended load. The turbulent water brings even coarser materials into suspension and the low temperature increases the viscosity of water, thereby reducing the falling velocity of suspended sediments (Drewry, 1986).

Wide seasonal and spatial variations in TSM concentration are observed in the Alaknanda basin (Fig. 8). Positive correlation occurs between discharge and suspended load. Suspended load is high during the high discharge period (June) and low during the low flow period. Such seasonal changes in the concentration of suspended sediment are caused by the increased competency of the water to carry sediment in suspension during the high flow season because of the more turbulent nature of water. The availability of suspended material is much higher in the source area in June (due to high discharge, increased cross section of stream area and availability of glacial debris) compared to October (characterized by reduced streamflow), indicating that bulk of the sediment transport occurs during the high flow period (June–September) from the glacierized basin. The study of Collins & Hasnain (1994) indicates that as flow rises, with increasing air temperature in spring and early summer, disproportionately large quantities of suspended sediments are transported in comparison to those moved later in the season. Major spatial instabilities of the subglacial drainage network punctuate the seasonal pattern of sediment flux particularly in the early part of the ablation period. The tributaries of Alaknanda are characterized by low suspended load and low seasonal fluctuation.

The suspended load is very high (2163 mg l<sup>-1</sup>) near the glacial portal region during high flow regimes and exhibits an irregular decrease downstream. The higher

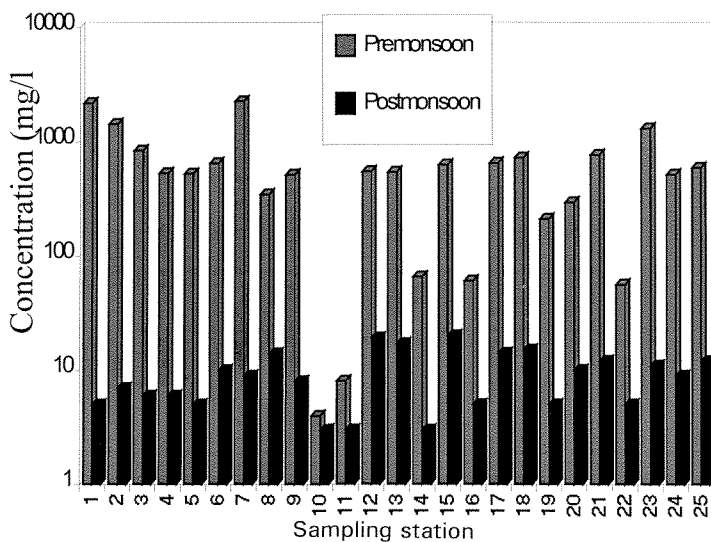


Fig. 8 Seasonal and spatial variation in TSM concentration.



concentration of TSM near the glacial portal region during high flow conditions and the irregular downstream decrease in TSM indicate that the twin glaciers, Satopanth and Bhagirath Kharak, are the major contributors of suspended load in the upper basin. Increased concentrations of suspended sediment at site 7 (Fig. 8) are due to the high elevational gradient between Badrinath (elevation 3411 m) and Pandukeshwar (elevation 1200 m). The more gentle gradients in the lower reaches of the river are reflected in the lower sediment concentrations.

### Chemical and physical denudation rate

High altitude Himalayan drainage systems show high rates of physical and chemical erosion. The chemical and physical denudation rate of the Alaknanda river basin is calculated from TDS and TSM contents, drainage area and water discharge (Table 4). The Alaknanda River at Devprayag delivers  $1.58 \times 10^6$  t of chemical load per year into the River Ganga, twice as much as than the Bhagirathi ( $0.74 \times 10^6$  t). The chemical denudation rate of Alaknanda basin is  $134 \text{ t km}^{-2} \text{ year}^{-1}$ , which is much higher than the Bhagirathi ( $95 \text{ t km}^{-2} \text{ year}^{-1}$ ), the Ganga ( $72 \text{ t km}^{-2} \text{ year}^{-1}$ ) and the Brahmaputra ( $105 \text{ t km}^{-2} \text{ year}^{-1}$ ). This is three times higher than the global average chemical denudation rate ( $36 \text{ t km}^{-2} \text{ year}^{-1}$ ). The annual suspended sediment transport of the Alaknanda is estimated to be  $4.20 \times 10^6$  t at Devprayag. The rate of sediment erosion of the Alaknanda basin is  $356 \text{ t km}^{-2} \text{ year}^{-1}$ . This is more than twice the world average ( $150 \text{ t km}^{-2} \text{ year}^{-1}$ ) and comparable to the average erosion rate of the Indian sub-continent ( $327 \text{ t km}^{-2} \text{ year}^{-1}$ ).

**Table 4** Average annual fluxes of TDS and chemical denudation rates (CDR) of Alaknanda and comparison with other selected rivers.

Rivers	Discharge ( $10^{12} \text{ l year}^{-1}$ )	Area ( $10^3 \text{ km}^2$ )	TDS ( $\text{mg l}^{-1}$ )	TDS flux ( $\times 10^6 \text{ t}$ )	CDR ( $\text{t km}^{-2} \text{ year}^{-1}$ )	References
Alaknanda	14.1	11.8	112	1.58	134	Present study
Bhagirathi	8.3	7.8	89	0.74	95	Pandey (1993)
Yamuna	93	140	222	21	150	Sarin <i>et al.</i> (1989)
Ganga	393	975	178	70	72	Sarin <i>et al.</i> (1989)
Brahmaputra	609	580	100	60	105	Sarin <i>et al.</i> (1989)
Global avge	31 400	101 000	115	3 611	36	Hu <i>et al.</i> (1982)

### CONCLUSIONS

The Alaknanda and its tributaries are alkaline in nature. Bicarbonate is the dominant anion and Ca and Mg are the dominant cations. Rock weathering is the most important mechanism controlling the water chemistry. The high concentrations of alkali earth metals, high alkalinity, and the high  $(\text{Ca}+\text{Mg})/(\text{Na}+\text{K})$  and  $(\text{HCO}_3)_c/(\text{HCO}_3)_s$  ratios indicate that the water chemistry of the basin is controlled largely by carbonate weathering and partly by silicate weathering. The seasonal and spatial variations in TDS are attributed to climatic and lithological control over the

ionic concentrations. The Alaknanda annually delivers  $1.58 \times 10^6$  t of dissolved load and  $4.20 \times 10^6$  t of suspended load to the Ganga. The high chemical and physical denudation rates are attributed to high relief, steep gradient, intense rainfall, favourable lithology and glacial activities.

**Acknowledgements** The authors are thankful to Dr D. S. Chauhan for his valuable suggestions. The financial assistance received as a JNU/UGC fellowship is gratefully acknowledged by A. K. Singh.

## REFERENCES

- Abbas, N. & Subramanian, V. (1984) Erosion and sediment transport in the Ganges river basin. *J. Hydrol.* **69**, 173–182.
- APHA (AWWA and WPCF) (1985) Standard methods for the examination of water and waste water. (16th edn) *Am. Public Health Assoc., Washington, DC*.
- Bahadur, J. (1988) Himalayan water from snow and glaciers. *Proc. First Nat. Wat. Comm.*, vol. II, 59–65. Ministry of Water Resource, Govt. of India.
- Berner, E. K. & Berner, R. A. (1987) *The Global Water Cycle: Geochemistry and Environment*. Prentice Hall, Englewood Cliffs, New Jersey.
- Bartarya, S. K. (1993) Hydrogeochemistry and rock weathering in a sub-tropical lesser Himalayan river basin in Kumaun, India. *J. Hydrol.* **146**, 149–174.
- Brijnjeel, L. A. & Bremmer, C. N. (1989) Highland–lowland interactions in the Ganga Brahmaputra river basin review of published literature. *ICIMOD Occasional Paper no. 11, Kathmandu, Nepal*, 136.
- Central Water Commission (1991) Discharge of Alaknanda River at Devprayag. Central Water Commission, New Delhi (unpublished).
- Chauhan, D. S. & Hasnain, S. I. (1993) Chemical characteristics, solute and suspended sediment loads in the meltwaters draining from Satopanth and Bhagirath Kharak glaciers, Ganga basin, India. In: *Snow and Glacier Hydrology* (ed. by G. J. Young) (Proc. Kathmandu Symp., November 1992), 403–410. IAHS Publ. no. 218.
- Collins, D. N. (1979) Hydrochemistry of meltwater draining from an Alpine glacier. *Arctic and Alpine Res.* **11**(3), 307–324.
- Collins, D. N. & Hasnain, S. I. (1994) Runoff and sediment transport from glacierized basin at the Himalayan scale. *Working Paper 15, Alpine Glacier Project, University of Manchester, UK*.
- Dasgupta, S. P. (1975) The flood plain of Ganga. In: *Upper Gangetic Flood Plain Calcutta* (ed. by S. P. Dasgupta), 1–7. Dept. of Sci. and Technol., National Atlas Organization.
- Drewry, D. (1986) *Glacial Geological Processes*. Edward Arnold, London, UK.
- Florence, T. M. & Farrar, Y. J. (1971) Spectrophotometric determination of chloride at the parts-per-billion level by the mercury (II) thiocyanate method. *Anal. Chim. Acta* **54**, 373–377.
- Gansser, A. (1964) *Geology of the Himalaya*. Interscience, London.
- Garrels, R. M. & Mackenzie, F. T. (1971) *Evolution of Sedimentary Rocks*. W. W. Norton, New York.
- Gibbs, R. J. (1970) Mechanisms controlling world water chemistry. *Science* **170**, 1088–1090.
- Gurnell, A. (1987) Suspended load. In: *Glacio-Fluvial Sediment Transfer* (ed. by A. Gurnell & M. J. Clark). John Wiley & Sons, New York.
- Handa, B. K. (1972) Geochemistry of Ganges river water. *Indian Geohydrol.* **8**, 71–78.
- Hasnain, S. I. (1992) Glaciofluvial sediment transfer from Chota Shigri, Himachal Pradesh. In: *Proc. Int. Symp. on Hydrology of Mountainous Areas* (Shimla, India), 273–283. NIH, Roorkee, India.
- Hasnain, S. I. (1996) Factor controlling suspended sediment transport in Himalayan glacier meltwaters. *J. Hydrol.* **181**, 49–62.
- Hasnain, S. I., Subramanian, V. & Dhanpal, K. (1989) Chemical characteristics of meltwaters from a Himalayan Glacier India. *J. Hydrol.* **106**, 98–106.
- Hasnain, S. I. & Renoj, J. T. (1996) Sediment transport and solute variation in meltwaters of Dokriani glacier (Bamak), Garhwal Himalaya. *J. Geol. Soc. India* **47**, 731–739.
- Hu, M., Stallard, R. F. & Edmond, J. M. (1982) Major ion chemistry of some large Chinese rivers. *Nature* **298**, 550–553.
- Pandey, S. K. (1993) Hydrochemistry of Bhagirathi (Proglacial) stream Garhwal Himalaya, India. Unpublished MPhil. dissertation, Jawaharlal Nehru Univ., New Delhi, India.
- Pandey, P. C., Pathak, J. K. & Bhatt, S. D. (1991) Ecology of the wetland pteridophytes of Kumaun Himalaya. In: *Ecology of the Mountain Waters*, 175–197. Asish Publ. House, New Delhi.

- Raiswell, R. (1984) Chemical models of solute acquisition in glacial meltwaters. *J. Glaciol.* **30**(104), 49–57.
- Raymahasay, B. C. (1986) Geochemistry of bicarbonate in the river water. *J. Geol. Soc. India* **27**, 114–118.
- Reynolds, R. C., Jr & Johnson, N. M. (1972). Chemical weathering in the temperate glacial environment of the Northern Cascade Mountains. *Geochim. Cosmochim. Acta* **36**, 537–554.
- Sah, M. P. (1991) Some geomorphic observations on Badrinath-Satopanth area, Chamoli district, Garhwal Himalaya. *Himalayan Geol.* **2**, 185–195.
- Sarin, M. M., Krishnaswamy, S., Dilli, K., Somayajulu, B. L. K. & Moore, W. S. (1989) Major ion chemistry of Ganga–Brahmaputra river system: weathering processes and fluxes of the Bay of Bengal. *Geochim. Cosmochim. Acta* **53**, 997–1009.
- Sarin, M. M., Krishnaswamy, S. K., Trivedi, J. R. & Sharma, K. K. (1992) Major ion chemistry of the Ganga source waters: weathering in the high altitude Himalaya. In: *Proc. Indian Acad. Sci. (Earth Planet. Sci.)* **1**, 89–98.
- Singh, A. K. (1993) Major ion chemistry of Alaknanda (Proglacial) stream, Garhwal Himalaya, India. Unpublished MPhil. dissertation, Jawaharlal Nehru Univ., New Delhi, India.
- Stallard, R. F. & Edmond, J. M. (1983) Geochemistry of the Amazon: the influence of the geology and weathering environment on the dissolved load. *J. Geophys. Res.* **88**, 9671–9688.
- Stumm, W. & Morgan, J. J. (1970) *Aquatic Chemistry*. Wiley Intersciences, New York.
- Subramanian, V. (1979) Chemical and suspended sediment characteristics of rivers of India. *J. Hydrol.* **44**, 37–55.
- Subramanian, V. & Dalvi, R. A. (1978) Some aspects of stream erosion in the Himalayas. *Himalayan Geol.* **9**, 822–834.
- Valdiya, K. S. (1980) Geology of the Kumaun lesser Himalaya. *Wadia Inst. of Himalayan Geology, Dehradun, India*.
- Vohra, C. P. (1993) Himalayan glaciers. In: *Harnessing the Eastern Himalayan Rivers. Regional Cooperation in South Asia* (ed. by B. G. Verghese & Ramaswamy R. Iyer). Kenark, New Delhi, India.

Received 12 August 1997; accepted 5 February 1998

