

Major ion chemistry of the Ganga-Brahmaputra river system: Weathering processes and fluxes to the Bay of Bengal

M. M. SARIN¹, S. KRISHNASWAMI¹, K. DILLI¹, B. L. K. SOMAYAJULU¹ and W. S. MOORE²

¹Physical Research Laboratory, Ahmedabad 380009, India

²University of South Carolina, SC 29208, U.S.A.

(Received July 15, 1988; accepted in revised form February 8, 1989)

Abstract—The Ganga-Brahmaputra, one of the world's largest river systems, is first in terms of sediment transport and fourth in terms of water discharge. A detailed and systematic study of the major ion chemistry of these rivers and their tributaries, as well as the clay mineral composition of the bed sediments has been conducted. The chemistry of the highland rivers (upper reaches of the Ganga, the Yamuna, the Brahmaputra, the Gandak and the Ghaghra) are all dominated by carbonate weathering; (Ca + Mg) and HCO₃ account for about 80% of the cations and anions. In the lowland rivers (the Chambal, the Betwa and the Ken), HCO₃ excess over (Ca + Mg) and a relatively high contribution of (Na + K) to the total cations indicate that silicate weathering and/or contributions from alkaline/saline soils and groundwaters could be important sources of major ions to these waters. The chemistry of the Ganga and the Yamuna in the lower reaches is by and large dictated by the chemistry of their tributaries and their mixing proportions.

Illite is the dominant clay mineral (about 80%) in the bedload sediments of the highland rivers. Kaolinite and chlorite together constitute the remaining 20% of the clays. In the Chambal, Betwa and Ken, smectite accounts for about 80% of the clays. This difference in the clay mineral composition of the bed sediments is a reflection of the differences in the geology of their drainage basins. The highland rivers weather acidic rocks, whereas the others flow initially through basic effusives.

The Ganga-Brahmaputra river system transports about 130 million tons of dissolved salts to the Bay of Bengal, which is nearly 3% of the global river flux to the oceans. The chemical denudation rates for the Ganga and the Brahmaputra basins are about 72 and 105 tons · km⁻² · yr⁻¹, respectively, which are factors of 2 to 3 higher than the global average. The high denudation rate, particularly in the Brahmaputra, is attributable to high relief and heavy rainfall.

INTRODUCTION

THE MAJOR ION CHEMISTRY of river waters reveals the nature of weathering on a basin-wide scale and helps us understand the exogenic cycles of elements in the continent-river-ocean system. Its importance has led to a number of detailed geochemical studies on some of the world's large and medium-size river systems, including the Amazon (GIBBS, 1972; STALLARD and EDMOND, 1983, 1987), the Mackenzie (REEDER *et al.*, 1972), the Mekong (CARBONNEL and MEYBECK, 1975) and the Chiang (HU *et al.*, 1982). In this paper we present data on the major ion chemistry of the Ganga-Brahmaputra river system and the clay mineral composition of their bedload sediments. These are two of the large rivers that drain the Indian subcontinent. On a global scale, the Ganga-Brahmaputra river system ranks first in terms of sediment transport and fourth in terms of water discharge to the world oceans (HOLEMAN, 1968; MILLIMAN and MEADE, 1983).

In spite of their global significance, the data that have been collected specifically for geochemical purposes from these river basins are limited. The Central Water and Power Commission of India (CWPC, 1973) has undertaken, from time to time, chemical investigations of these river waters to assess their suitability for domestic, industrial and agricultural uses. HANDA (1972, 1978), RAYMAHASHAY (1973), SUBRAMANIAN (1979, 1985), and ABBAS and SUBRAMANIAN (1984) have measured the chemical composition of the Ganga and Brahmaputra, as well as some of their tributaries, to assess the erosion rates of the Indian subcontinent and to determine the flux of major elements transported by these rivers to the world oceans.

A detailed geochemical study of the Ganga-Brahmaputra river system was initiated in 1982 (SARIN and KRISHNASWAMI, 1984) with the following objectives:

- i) to identify the sources of major ions to these rivers in terms of atmospheric supply and chemical weathering of rocks and soils of the drainage basin;
- ii) to determine the flux of dissolved major ions transported by these rivers to the Bay of Bengal;
- iii) to study the clay mineralogy of the river sediments from the source to the estuary, and to understand the relationship between mineralogy and water chemistry; and
- iv) to determine the parameters controlling the supply of uranium (²³⁸U, ²³⁴U) and radium (²²⁶Ra, ²²⁸Ra) isotopes to river waters during weathering, and to determine their fluxes to the estuaries.

In this paper we present data only on the major ion chemistry and clay mineralogy; the results of U and Ra isotope measurements will be reported in a subsequent publication.

GEOHYDROLOGY

The Ganga river drainage basin occupies an area of about 10⁶ km² of the Indian subcontinent (RAO, 1975). It is bounded on the north by the Kumaun Himalayas and to the south by the Vindhya, the Indo-Gangetic alluvial plains and the Vindhyan Bundelkhand Plateau (Fig. 1). The source of the Ganga, the Gangotri glacier in the Kumaun Himalayas, is at an elevation of about 7000 m. The main stream of the Ganga is formed at Devprayag after the confluence of the Bhagirathi and Alaknanda rivers. The river then descends to the alluvial plains after cutting across the Siwalik range at Hardwar. Among the major tributaries, the Gomti, the Ghaghara and the Gandak join the Ganga from the north, whereas the Yamuna and the Son join from

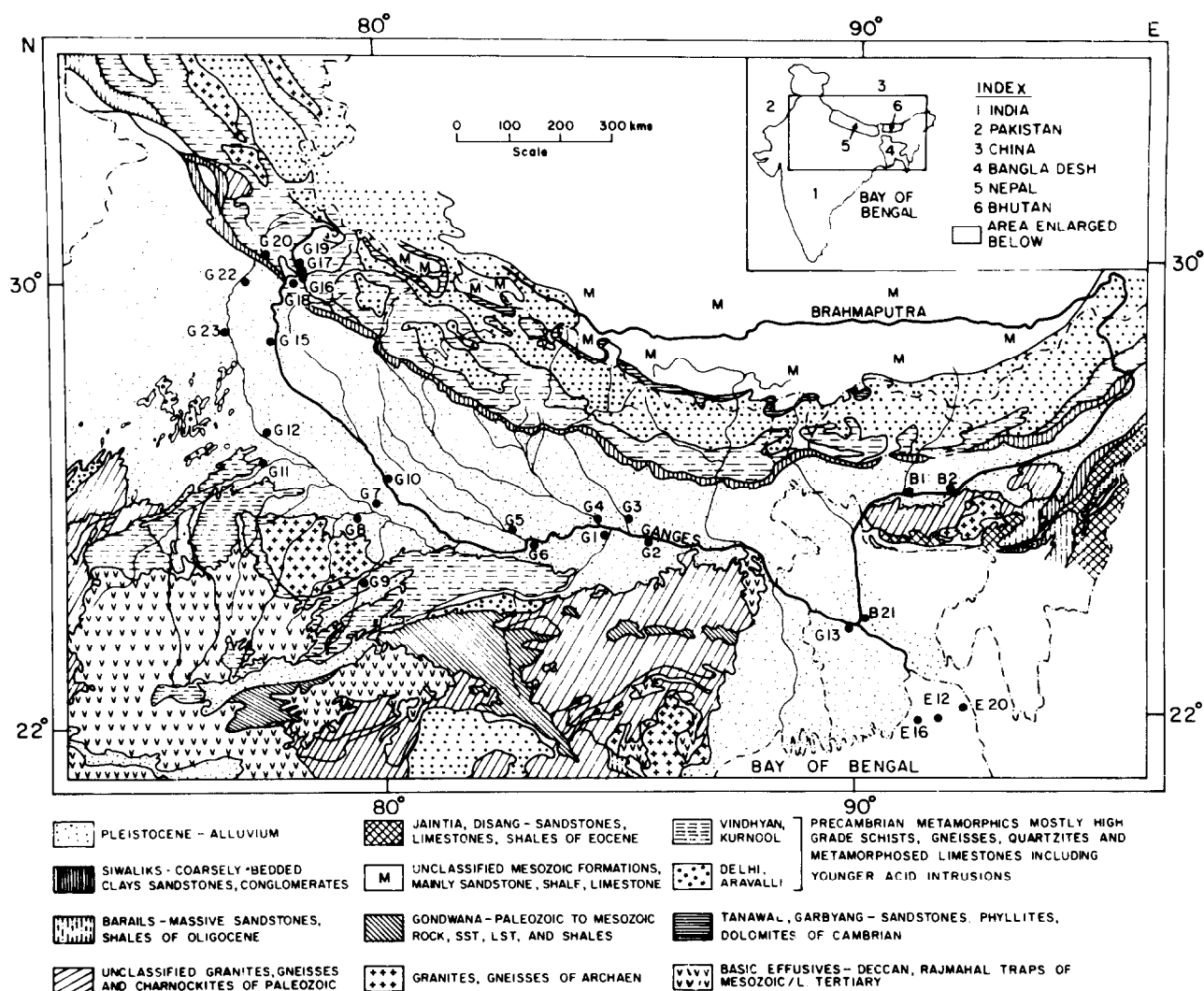


FIG. 1. Geologic and lithologic map of the Ganga and Brahmaputra river drainage basins.

the south (Fig. 2). The Chambal, the Betwa and the Ken are the major tributaries of the Yamuna (Fig. 2). The primary source of water to all these rivers is precipitation during the southwest monsoon (July–September). However, in the southern tributaries, the flow during summer months (March–June) is mainly sustained by the effluent seepage of groundwaters. The mean annual discharge of the Ganga during 1949 to 1960 (UNESCO, 1971) at Farakka was $393 \cdot 10^{12} \text{ l} \cdot \text{yr}^{-1}$. Of this, 25.4% of the flow occurs in September, 4.8% in November, 3% in December and 1.5% in March, the four months during which our samples were collected for chemical analysis. Nearly 60% of the water flowing in the Ganga comes from the drainage areas north of the river (RAO, 1975).

Several types of geological features have been recognized in the Kumaun Himalayas. The outer Kumaun Himalayas (Fig. 1) are composed of sediments of Miocene to Pleistocene age (the Siwaliks). The Siwalik sediments constitute a large thickness of detrital rocks such as coarsely bedded sandstones, clays and conglomerates. In the central-lower Himalayas, there are three main zones (Fig. 1): (i) the outer Krol belt of Upper Carboniferous age—consisting of dolomitic limestones, calcareous shales and sandstones, with a large replacement of limestones by gypsum in many places; (ii) the inner sedimentary belt (Deoban-Tejam zone) of thick limestones, overlain by a sequence of shales and quartzites; and (iii) a zone of metamorphic and igneous “crystalline rocks” separating the two units above. These rocks are dominated by biotite-chlorite, Augen gneisses and granites (GANNSE, 1964; VALDIYA, 1980; WADIA, 1981).

In the lower reaches, the Ganga drainage basin is characterized by alluvial plains (Fig. 1) consisting of massive beds of clay, sand and gravel. The clay zones of the alluvial plains contain impure calcareous matter in the form of irregular concretions, locally known as “kankar”. The abundance of calcareous matter in some of these regions is as high as 30% (WADIA, 1981). A large part of the soils in the alluvial plains (where the annual rainfall is less than 100 cm) is impregnated with alkaline and saline salts (Fig. 3). The alkaline soils contain sodium bicarbonate and carbonate, among the soluble salts, while the saline soils have sodium chloride and sulphate as their main soluble component (BHARGAVA *et al.*, 1981; BHARGAVA and BHATTACHARJEE, 1982). The groundwaters in these areas are the main source of soil salinization.

The watersheds of the Chambal, Betwa, Ken and Son rivers lie mainly in the Vindhyan-Bundelkhand plateau. This region forms a part of the Archean shield and is made of crystalline igneous and metamorphic rocks (Fig. 1). Based on their texture and composition, several types of granites have been recognized in Bundelkhand plateau. The Vindhyan system is largely composed of limestones, shales, sandstones and recent alluvial deposits. The headwaters of the Chambal, the Betwa and Ken rivers, and a part of their drainage area, are in the Deccan Traps.

The Brahmaputra river originates from the Chamyungdung glacier at an elevation of 5200 m in the Tibetan Himalayas. After flowing parallel to the main Himalayan range, it descends into the Assam valley (Figs. 1, 2). The Ganga and the Brahmaputra merge in Ban-

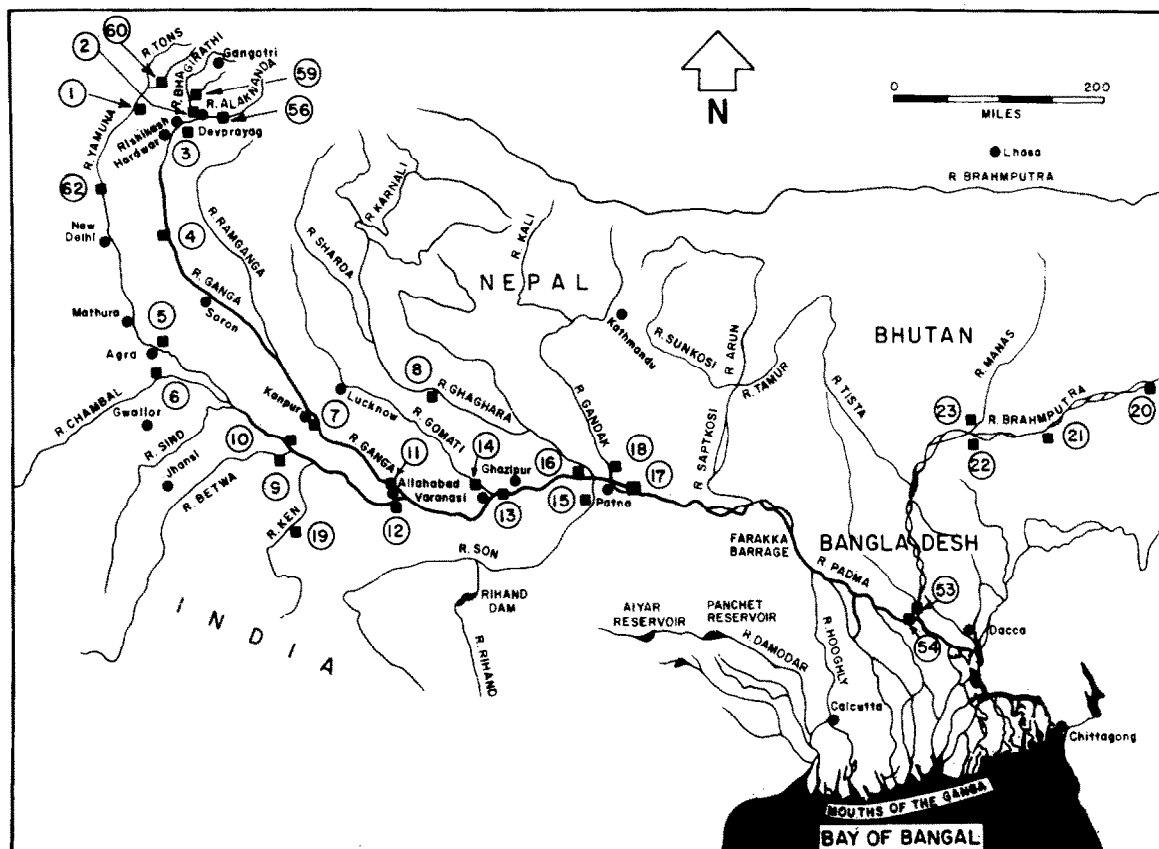


FIG. 2. Sample location map. Numbers correspond to the sampling sites; see Table 2. In all, 62 samples were collected during March, September and December 1982, and November 1983.

gladesh and subsequently break up into a number of distributaries before their outfall into the Bay of Bengal (Fig. 2). The water discharge data for the Brahmaputra river at Gauhati (*Hydrology Review*, 1976) shows that the moderate/peak discharge occurs between April and October and accounts for 86% of the total annual discharge. The remaining 14% occurs during the lean flow period: November through March.

The geological information on the Tibetan Himalayas is limited. The lithology of the southern slopes of the Tibetan Himalayas along the course of the Brahmaputra river is dominated by reduced shales, gneisses and volcanic rocks. The river drainage basin in the Assam valley is characterized by recent and Pleistocene alluvium. In the central part of the valley, the river encounters the granite and gneiss projections of the Mikir Hills (Fig. 1).

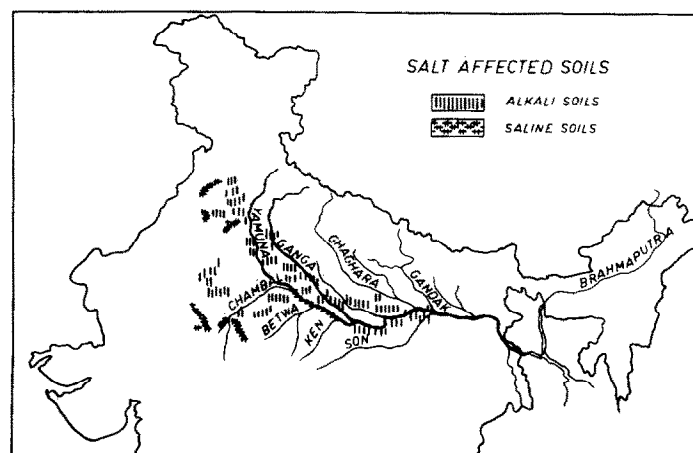


FIG. 3. Map of the distribution of alkaline and saline soils in the Ganga river drainage basin (adapted from the map published by CSSRI, 1975).

TABLE-1 EXPERIMENTAL METHODS

Parameter	Method	Reference
pH	in situ probe	Sarin (1983)
Conductance	Conductometer at site	"
Bicarbonate	Acid titration at site	"
Chloride	AgNO ₃ titration and/or mercuric thiocyanate, colorimetry	Florence and Farrar (1971)
Sulphate	BaCl ₂ titration	Analytical methods Manual, Environment Canada (1979)
Na, K, Mg, Ca	Flame AAS	Perkin Elmer Handbook (1976)
Silica	Molybdenum blue, Spectrometry	Strickland and Parsons (1972)
Clay Minerals	X-ray diffraction on <2 μ m fraction	Biscaye (1965); Matter (1974)

Errors associated with the measurement of major ions are < 5%.

SAMPLING AND METHODOLOGY

This study was undertaken to determine the major ion chemistry of the Ganga and Brahmaputra rivers and their tributaries, as well as the clay mineralogy of the bed sediments. The samples were collected from several locations (Figs. 1, 2) along the Ganga main stream and its tributaries during different seasons (March, September and December 1982, and November 1983) representing lean, peak and moderate flow conditions. Samples of shallow groundwaters from the Ganga basin were also collected during November 1983. The Brahmaputra and Manas rivers were sampled during April and December 1982, representing their moderate and lean flows. All samples were filtered on site within five to six hours of collection and stored in polyethylene containers. The procedures adopted for the measurement of the dissolved constituents are given in Table 1 (SARIN, 1983). The suspended matter separated from large volume water samples and bed sediments collected (Fig. 1) from the river banks were used for clay mineralogical studies. These samples were size

fractionated and the <2 μ m size fraction was used for clay mineral analysis by X-ray diffraction. The relative percentages of clay minerals were determined following the techniques of BISCAYE (1965) and MATTER (1974).

RESULTS

1. Major ion chemistry

The data on the major ion composition of the Ganga-Brahmaputra rivers and their tributaries are given in Table 2. The analytical precision for the measurement of major ions is better than $\pm 5\%$. The observed charge balance between cations (TZ⁺) and anions (TZ⁻) is an added proof of the precision of our data. Statistical analysis of the data show that the TZ⁺ and TZ⁻ are coupled by the relation

TABLE 2 MAJOR ION COMPOSITION OF THE GANGA AND BRAHMAPUTRA RIVERS AND THEIR TRIBUTARIES

River, # (Location)	Sampling Date	Na	K	Mg	Ca	HCO ₃	Cl	SO ₄	SiO ₂	TDS
					(μ mole.l ⁻¹)					(mg.l ⁻¹)
Bhilaranga, 59* (Tehri)	11/83	149	46	130	392	1037	11	-	-	-
Alaknanda, 56* (Bagwan)	11/83	122	49	238	544	1426	13	-	-	-
Bhagirathi, 2* (Devprayag)	03/82	141	37	160	300	854	42	95	157	93
	11/83	172	52	184	473	1123	31	-	-	-
GANGA MAIN CHANNEL										
Ganga, 3* (Rishikesh)	03/82	145	40	239	398	1004	42	162	152	114
	09/82	59	38	153	353	894	23	121	109	94
	11/83	137	52	238	544	1382	21	-	-	-
Ganga, 4* (Gurhmukteshwar)	03/82	322	81	329	612	1891	58	190	191	190
	09/82	105	68	182	471	1159	19	143	127	121
	11/83	332	75	356	789	2376	30	-	-	-
[G.W.]§	11/83	1693	159	1134	1238	6372	38	-	-	-
Ganga, 7 (Kanpur)	03/82	776	100	494	683	2943	168	214	118	274
	09/82	354	82	242	565	1829	78	103	157	173
	11/83	1140	107	713	1227	4536	218	-	-	-
Ganga, 11 (Allahabad)	03/82	1060	105	531	560	2637	291	245	71	263
	09/82	425	79	201	458	1570	116	85	121	151
Ganga, 13 (Varanasi)	03/82	2121	100	695	690	3903	797	331	93	401
	09/82	473	62	188	514	1707	162	72	147	164
	12/82	2185	88	724	696	4047	820	278	224	415
	11/83	1487	94	637	1134	4104	591	-	-	-
[G.W.]	11/83	984	70	1297	1526	6480	40	-	-	-
Ganga, 16 (upstream Patna)	03/82	1767	95	675	666	3567	607	264	160	361
Ganga, 17 (Patna)	03/82	1096	86	593	760	3232	400	203	147	313
	09/82	280	63	203	547	1707	87	58	129	156
	12/82	1092	75	543	790	3135	361	148	197	303
	11/83	702	83	497	970	3132	217	-	-	-
[G.W.]	11/83	759	136	918	1651	5724	93	-	-	-
Ganga, 54 (Aricha Ghat)	11/83	614	84	410	923	2851	175	-	-	-

TABLE-2 Contd.....

River, #	Sampling	Na	K	Mg	Ca	HCO ₃	Cl	SO ₄	SiO ₂	TDS
(Location)	Date	(μmole.l ⁻¹)					(mg.l ⁻¹)			
<u>YAMUNA MAIN CHANNEL</u>										
Yamuna, 60*										
(Mussorie)	11/83	206	48	367	923	1944	397	-	-	-
[G.W.]	11/83	61	26	2332	2858	3542	25	-	-	-
Yamuna, 1*	03/83	203	45	329	590	1677	52	251	168	176
(Saharanpur)	11/83	343	91	745	1436	4104	43	-	-	-
[G.W.]	11/83	1072	1814	1037	1288	5832	639	-	-	-
Yamuna, 62										
(Sonipat)	11/83	534	91	605	1093	3197	100	-	-	-
[G.W.]	11/83	2288	131	821	1822	6048	417	-	-	-
Yamuna, 5	03/82	672	89	370	698	1891	400	331	166	227
(Agra)	09/82	1401	130	395	794	1921	1172	412	170	287
	11/83	4980	206	1393	1327	3542	4546	-	-	-
[G.W.]	11/83	1346	31	1997	1151	4104	724	-	-	-
Yamuna, 10	03/82	1529	107	539	710	2683	775	431	145	322
(Hamirpur)	11/83	2525	102	842	1072	4536	1275	-	-	-
Yamuna, 12	03/82	2775	87	778	702	4285	1163	379	123	461
(Allahabad)	09/82	556	57	190	547	1753	222	67	164	173
	12/82	2622	81	787	967	4427	1128	321	253	477
<u>GANGA TRIBUTARIES</u>										
Chambal, 6	03/82	1971	68	555	610	3095	594	936	83	333
(Dholpur)	09/82	593	53	337	829	2531	284	76	296	247
	11/83	1773	81	583	923	3542	698	-	-	-
[G.W.]	11/83	7246	34	1825	1112	9612	2104	-	-	-
Betwa, 9	03/82	2377	53	690	502	4238	426	71	237	388
(Hamirpur)	11/83	1514	57	609	1005	4320	355	-	-	-
[G.W.]	11/83	5339	51	1814	1758	10260	1210	-	-	-
Ken, 19	03/82	701	54	461	550	2683	233	52	214	241
(Patna)	11/83	1121	48	529	1099	3802	318	-	-	-
Gomti, 14	03/82	1149	99	695	794	3644	258	255	210	347
(Dobni)	11/83	1228	69	767	1011	4234	235	-	-	-
[G.W.]	11/83	8276	85	1015	1558	8856	3026	-	-	-
Son, 15	03/82	458	58	313	610	2165	200	52	235	103
(Ara)	09/82	240	40	166	434	1372	71	22	210	129
	11/83	423	49	302	836	2376	207	-	-	-
[G.W.]	11/83	1171	28	497	1956	5508	69	-	-	-
Ghaghara, 8*	03/82	299	70	453	729	2637	42	114	172	233
(Ayodhya)	09/82	96	59	232	528	1601	26	76	114	144
	11/83	267	74	497	1029	2808	21	-	-	-
[G.W.]	11/83	1373	51	1069	1212	5616	39	-	-	-
Gandak, 18*	03/82	251	88	411	682	2013	149	264	166	210
(Hajipur)	09/82	74	84	259	649	1860	32	103	143	170
	11/83	156	78	389	818	2074	102	-	-	-
[G.W.]	11/83	1705	78	1069	2757	7668	423	-	-	-
<u>BRAHMAPUTRA</u>										
Brahmaputra, 20*	04/82	73	56	163	370	1021	19	113	172	107
(Dibrugarh)										
Brahmaputra, 21*	04/82	78	46	145	373	884	26	99	122	91
(Gauhati)	12/82	163	57	208	541	1368	40	148	202	144
Brahmaputra, 22*	04/82	80	46	148	318	884	29	99	118	92
(Goalpara)	12/82	164	58	214	553	1406	40	148	204	147
Manas, 23*	04/82	94	42	181	348	930	26	113	131	99
(Goalpara)										
Brahmaputra, 53	11/83	153	64	227	643	1642	17	-	-	-
(Aricha Ghat)										

Number corresponds to the sampling location, Fig.2.

* Denotes samples that are grouped as Highland Rivers, other samples are Lowland Rivers.

\$ Groundwater collected from an adjacent location.

$$TZ^+ (\mu\text{Eq/l}) = 0.96 TZ^- (\mu\text{Eq/l}) + 24.7$$

with a correlation coefficient of 0.998 for 40 data points (data from the November 1983 sampling is not included for the statistical analysis, since sulphate was not measured in these samples). In the above discussion it is implicit that the contribution of ions other than those measured are insignificant for the cation and anion charge balance. This assumption

seems valid from the data of HANDA (1972, 1978) and the Central Water and Power Commission of India (CWPC, 1973) which show that concentrations of other ions such as NO₃ and PO₄ in these waters are quite low.

II. Water temperature, pH and specific conductance

The observed temperature of the waters varied from 13 to 30°C. The colder waters were from the upper reaches of the

Ganga and the Yamuna rivers, which is to be expected considering their proximity to glacier sources and local climate. The pH values of the Ganga river water and its tributaries range between 7.6 and 8.4, similar to those reported earlier (CWPC, 1973). The pH of the Brahmaputra waters varies from 7.2 to 7.6. The specific conductance measured in these river waters ranges between 107 and 622 $\mu\text{mhos/cm}$, the high values occurring during lean flow conditions. The total dissolved salt content of the rivers is linearly correlated with specific conductance.

III. Clay mineralogy

The relative percentages of the four clay mineral groups (smectite + illite + kaolinite + chlorite = 100%) in the <2 μm fraction of the bed sediment samples are given in Table 3.

DISCUSSION

The results of the present study on the dissolved and suspended phases of the Ganga and Brahmaputra rivers have been synthesised to determine (i) the source of major ions to

these river waters and their relation to regional geology and weathering processes, and (ii) the fluxes of major ions to the Bay of Bengal *via* these rivers. Based on the relief, rivers have been classified into two groups:

Highland rivers: Bhagirathi, Ganga (up to Garhmukteshwar), Yamuna (up to Saharanpur), Ghaghara, Gandak, Brahmaputra (up to Goalpara) and Manas.

Lowland rivers: Yamuna (at Agra), Yamuna (at Allahabad), Chambal, Betwa, Ken, Son, Gomti and Ganga (downstream of Garhmukteshwar).

Sources of major ions to the Ganga and Brahmaputra Rivers

I. Atmospheric contribution to the major ion chemistry. Several earlier studies (HOLLAND, 1978; MEYBECK, 1979; STALLARD and EDMOND, 1981) have shown that the atmospheric supply of chemical constituents to river water can be substantial. The atmospheric supply consists of three principal components: marine, terrestrial and anthropogenic. The marine component consists of Na, K, Mg, Ca, Cl and SO_4 in approximately sea-salt proportions. The terrestrial and an-

TABLE 3 RELATIVE ABUNDANCE OF CLAY MINERALS IN RIVER SEDIMENTS

River, # (Location)	SMECTITE (%)	ILLITE (%)	KAOLINITE (%)	CHLORITE (%)
Bhilarua, G19 (Tehri)	ND	80.0	10.7	9.3
Bhagirathi, G17 (Devprayag)	ND	77.7	13.6	8.7
GANGA MAIN CHANNEL				
Ganga, G18 (Rishikesh)	ND	75.5	12.8	11.7
Ganga, G15 (Garhmukteshwar)	22.5	56.3	11.4	9.8
Ganga, G10 (Kanpur)	35.4	53.2	6.3	5.2
Ganga, G6 (Varanasi)	78.2	15.1	3.4	3.3
Ganga, G2 (Patna)	60.8	25.7	5.8	7.7
Ganga, G13 (Aricha Ghat)	56.2	31.9	5.4	7.0
YAMUNA MAIN CHANNEL				
Yamuna, G20 (Mussoorie)	ND	79.6	10.6	9.8
Yamuna, G22 (Saharanpur)	58.4	29.6	6.3	5.7
Yamuna, G23 (Sonapat)	17.0	68.0	7.8	7.2
Yamuna, G12 (Agra)	25.0	58.4	9.2	7.4
Yamuna, G7 (Hamirpur)	71.1	22.4	3.2	3.2
GANGA TRIBUTARIES				
Chambal, G11 (Dholpur)	87.8	7.6	2.3	2.4
Betwa, G8 (Hamirpur)	87.1	8.8	1.9	2.0
Ken, G9 (Patna)	88.7	6.5	2.4	2.4
Gomti, G5 (Dobni)	26.1	61.1	6.5	6.3
Son, G1 (Ara)	ND	52.6	22.1	25.3
Chaghara, G4 (Ayodhya)	19.2	59.2	11.7	10.0
Gandak, G3 (Hajipur)	16.9	62.2	13.4	7.5
BRAHMAPUTRA				
Brahmaputra, B2 (Gauhati)	ND	62.5	18.8	18.8
Brahmaputra, B1 (Goalpara)	ND	57.1	22.7	20.2
Brahmaputra, B21 (Aricha Ghat)	15.2	61.7	12.3	10.9

Number corresponds to the sampling location, see Figure 1.

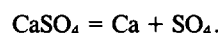
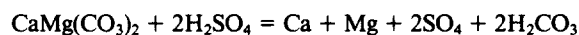
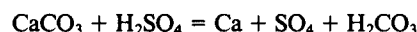
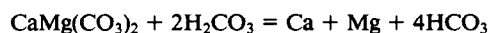
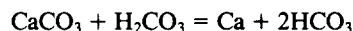
ND : Not Detectable.

thropogenic sources are relatively difficult to characterize and can make a significant contribution of K, Ca and SO_4 to the river water chemistry. The ideal approach to determine the atmospheric input to river waters would be to measure the average chemical composition of local precipitation. In this study, the chemical analysis of rain water has not been done. However, we have estimated the marine component of the major ions based on available data (HANDA 1968; SEQUEIRA and KELKAR, 1978) on the chemistry of monsoon rain water over India. We have used chloride as a reference and have assumed that all the chloride in the highland rivers during their peak discharge is of marine origin. The marine component of Na, K, Mg, Ca and SO_4 (during peak flow) is then calculated (Table 4) from the observed ratio (SEQUEIRA and KELKAR, 1978) of major ions to chloride in the rain waters of coastal stations (see SARIN, 1983, for a detailed compilation). Our estimate (Table 4), based on the above assumption, would be an upper limit since it neglects the contribution of chloride, if any, from dissolution of evaporites present in the drainage basin. However, the observation that the abundance of chloride in the highland rivers during peak flow ($23\text{--}32 \mu\text{mole}\cdot\text{l}^{-1}$; Table 4) is similar to that in the rain waters of inland stations ($18\text{--}41 \mu\text{mole}\cdot\text{l}^{-1}$; SEQUEIRA and KELKAR, 1978) seems to indicate that the contribution of chloride from evaporites is insignificant.

In contrast, such an assumption may not be valid for the lowland rivers that flow through the alkaline and saline salt affected soils. The concentration of chloride in the lowland rivers during their peak flow (Table 4) is significantly higher than that observed in rain waters from nearby inland stations, suggesting additional sources of chloride to these waters. We have estimated the marine component of chloride (and other major ions) in the lowland river by assuming that the decrease in chloride concentration with distance from a "moisture front" for the highland and lowland rivers is of the same magnitude (SARIN, 1983). These estimated values (Table 4) suggest that the contribution of marine salts to the major ion chemistry of the rivers (within the Ganga drainage basin) is insignificant relative to the weathering processes. This inference is also borne out from the Na:Cl ratio, which is much

higher (ranges between 1.7 and 13; average ~ 3) than that observed for rain water samples from inland stations.

II. Major ion chemistry and chemical weathering processes. Mass balance models provide a convenient, though not unique, approach to inferring the sources of dissolved major ions to river waters. The abundances of dissolved major cations (Na, K, Mg and Ca) and anions (HCO_3 , SO_4 and Cl) in river waters can be modeled in terms of the weathering of various minerals in the drainage basin. Some weathering reactions for minerals such as calcite (CaCO_3), dolomite ($\text{CaMg}(\text{CO}_3)_2$) and gypsum (CaSO_4) can be written as (GARRELS and MACKENZIE, 1971; HOLLAND, 1978):



If the weathering is by carbonic acid, the equivalent ratio of dissolved Ca: HCO_3 in the waters resulting from calcite weathering is 1:2, whereas for dolomite weathering it is 1:4. If sulphuric acid is the weathering agent, then the Ca: SO_4 ratio in the waters would be 1:1 for calcite and 1:2 for dolomite.

The solution products of silicate weathering are more difficult to quantify because the degradation of silicates is incongruent, generating a variety of solid phases (mostly clays) along with dissolved species. A general reaction for weathering of silicate rocks with carbonic acid can be written as:



The quantities of cations and anions released to solution are determined by the proton source, composition of the parent rock and the solid products of the chemical weathering. However, there can be distinctly different weathering reac-

TABLE 4 ESTIMATED CONTRIBUTION OF MARINE SALTS TO RIVER WATERS

River, # (Location)	Measured ^{\$} Cl	Cyclic ^{\$} Cl	Cl	Na	K (Percent Cyclic)	Mg (Percent Cyclic)	Ca	SO ₄
Highland Rivers⁺								
Ganga, 3 (Rishikesh)	22.6	22.6	100	27	1.3	2.2	1.7	1.6
Ghaghara, 8 (Ayodhya)	25.8	25.8	100	23	1.2	2.0	1.5	3.4
Gandak, 18 (Hajipur)	32.3	32.3	100	37	1.0	2.2	1.5	3.1
(Average)	-	-	(100)	(29)	(1.2)	(2.1)	(1.6)	(2.7)
Lowland Rivers⁺								
Yamuna, 5 (Agra)	1172	23	2	1.4	0.5	1.0	0.9	0.6
Yamuna, 12 (Allahabad)	222	29	13	4.4	1.4	2.7	1.6	4.3
Chambal, 6 (Dholpur)	284	23	8	3.4	1.2	1.2	0.9	3.1
Son, 15 (Ara)	71	32	45	11	2.3	3.5	2.3	14

Number corresponds to the sampling location, see Figure 2 and Table 2

\$ In units of $\mu\text{mol}\cdot\text{l}^{-1}$

+ Estimated contribution during peak flow conditions

tions which can generate similar solution composition. For example, the relative proportions of Ca and HCO_3 released during the weathering of calcium silicate (anorthite) is the same as that resulting from calcite dissolution. Therefore, water chemistry alone cannot identify the source of major ions unambiguously. Additional information on the geology of the terrain and mineralogy of the associated suspended phases and sediments would help constrain the source minerals and weathering reactions. In the following discussion we have made an attempt to infer the likely sources of major ions to the Ganga and Brahmaputra rivers based on water chemistry, regional geology of the basin, mineralogy of the river sediments and the mass balance approach discussed above.

In the highland rivers, calcium and magnesium are the major cations, together accounting for 82 to 92% of the cations (Table 2, Fig. 4). Among anions, bicarbonate is the most dominant, with minor contributions from sulphate and chloride, $\sim 10\%$. The lowland rivers during peak flow, have a composition similar to the highland waters, with calcium, magnesium and bicarbonate being the most abundant ions. However, the contribution of $(\text{Na} + \text{K})$ and $(\text{SO}_4 + \text{Cl})$ to the major ion composition of the lowland rivers is more pronounced during lean and moderate flow conditions (Table 2, Figs. 4, 5). The silica concentration ranges between 114 and $204 \mu\text{mole} \cdot \text{l}^{-1}$ and 83 to $296 \mu\text{mole} \cdot \text{l}^{-1}$ in the highland and lowland rivers, respectively (Table 2).

Figure 6 is a plot of $(\text{Ca} + \text{Mg})$ vs. HCO_3 , the equiline by and large divides the highland waters from the lowland waters.

Most of the samples of the highland rivers lie slightly above the equiline, the average $(\text{Ca} + \text{Mg})/\text{HCO}_3$ equivalent ratio being 1.09 ± 0.1 . Both silicate weathering and carbonate dissolution can yield such a composition. However, considering that $(\text{Ca} + \text{Mg})/\text{TZ}^+$ ratio is 0.9 , for silicate weathering to be the primary source of $(\text{Ca} + \text{Mg})$ it would require the terrain to be dominated by alkaline earth silicates. But, this is not reflected in the regional geology of the drainage basin. We attribute the abundance of $(\text{Ca} + \text{Mg})$ in the highland rivers to carbonate weathering.

In the lowland rivers, $(\text{Ca} + \text{Mg})$ falls below the $1:1$ trend, the departure from the equiline being more pronounced during the lean flow season (Fig. 6). This observation requires part of the carbonate alkalinity to be balanced by alkalis. The Chambal, Ken and Son drainage basins include limestones and dolomites of the Vindhyan system, while the Yamuna river (between Saharanpur and Allahabad) flows through alluvial plains containing "kankar" carbonates. Such a regional geology could favour dissolution of carbonate as a probable source for $(\text{Ca} + \text{Mg})$ in these rivers. The $(\text{Na} + \text{K})$ required to balance part of the carbonate alkalinity (Fig. 6) can be supplied from silicate weathering and/or via seepage of alkaline groundwaters.

Despite the perennial rivers, the Indo-Gangetic alluvial plain lacks a well-developed surface drainage system. As a result, part of the runoff is lost through evaporation during summer months. The cyclic wetting and drying in some areas aids the formation of alkaline/saline soils and saline groundwaters in the drainage basins (Fig. 3). Such alkaline soils/

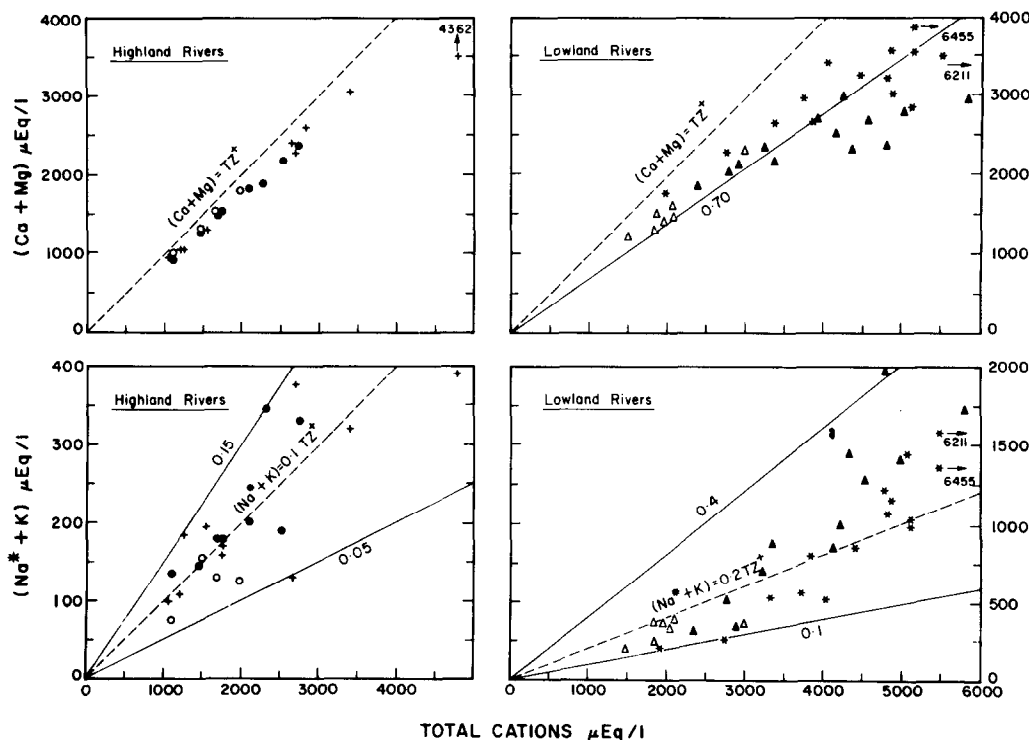


FIG. 4. Scatter diagrams of $(\text{Na}^+ + \text{K})$ and $(\text{Ca} + \text{Mg})$ vs. total cations (TZ^+) for the highland and lowland rivers. Na^+ is Na corrected for chloride. $(\text{Ca} + \text{Mg})$ accounts for most of the cations in the highland rivers. In the lowland rivers, the data fall significantly below the $1:1$ trend, indicating a larger contribution of alkalis to the major ions. *Symbol key:* Highland Rivers: $\bullet$ Lean, $\circ$ peak and $+$ moderate flows; Lowland Rivers: $\blacktriangle$ Lean, $\triangle$ peak and $*$ moderate flows.

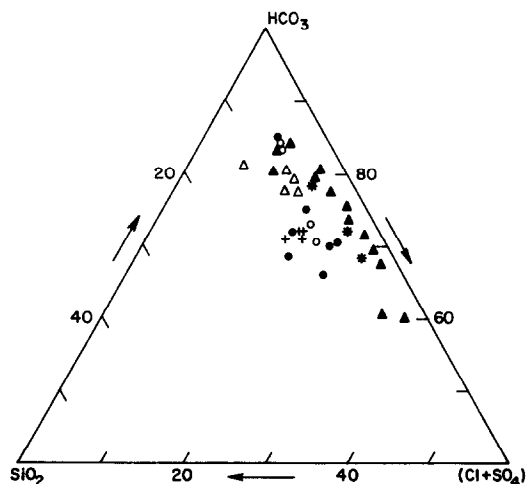


FIG. 5. Triangular plot representing the relative abundances of SiO_2 , $(\text{SO}_4 + \text{Cl})$ and HCO_3 (units of $\mu\text{Eq} \cdot \text{l}^{-1}$) in the highland and lowland rivers. In the lowland rivers, during their lean flow, high concentrations of $(\text{SO}_4 + \text{Cl})$ are due to contribution from soil salts.

groundwaters can serve as a source of sodium bicarbonate/carbonate to the rivers. Another observation is that in both the Chambal and the Yamuna (at Allahabad) the $(\text{Ca} + \text{Mg}):(\text{Na} + \text{K})$ ratio decreases during lean flow, resulting mainly from an increase in sodium concentration (Table 2). This increase in sodium is paralleled by a corresponding increase in $(\text{SO}_4 + \text{Cl})$, suggestive of a common source for these ions, such as saline groundwaters and/or dissolution of soil salts. Preliminary studies on the chemistry of groundwaters from some of these river basins (Table 2) attest to this hypothesis. The results show that groundwaters from the Chambal, Betwa and Gomti basins are alkali rich, $(\text{Na} + \text{K})$ contributing $\sim 50\%$ of the cations.

The major ion chemistry of the Ganga main channel is controlled by the composition of its tributaries. This is clearly discernible from the downstream variations in the major ion composition of the main channel during lean flow (Fig. 7). For example, there is a significant increase in sodium content along the Ganga main stream between Rishikesh and Varanasi (Table 2, Fig. 7). Further downstream, with the confluence of the highland rivers, the Ghaghara and the Gandak, sodium content decreases. During the lean period, $(\text{Cl} + \text{SO}_4)$

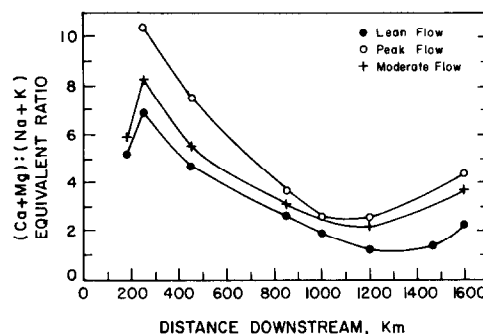


FIG. 7. Downstream and seasonal variations in $(\text{Ca} + \text{Mg}):(\text{Na} + \text{K})$ ratio in the Ganga main stream. The downstream variation results from the mixing of various tributaries.

is more significant in the anion balance, chloride being particularly more enhanced (Fig. 5). This increase in sodium, chloride and sulfate concentrations along the main channel indicates that during lean flow there is a significant contribution of major ions from soil salts/groundwaters. During peak flow, the downstream variations in the major ion abundances are less pronounced. Calcium and magnesium account for about 80% of the cations, whereas bicarbonate accounts for 80 to 90% of the anions. Following the arguments presented earlier, we infer that during peak flow, the chemistry of the Ganga main channel (between Hardwar and Patna) is dictated by carbonate weathering. A comparison of our results for the Ganga main channel at Allahabad (September 1982 data) with those of *ABBAS and SUBRAMANIAN (1984)* seems to show a similar trend. However, it is not possible to make any quantitative comparisons since their data show a significant difference between TZ^- and TZ^+ .

Another notable observation pertaining to the lowland rivers is the doubling of the Mg/Ca ratio during their lean flow. The Mg/Ca ratio averages about 0.4 during peak flow and nearly doubles to 0.8 during lean flow, a trend similar to that observed by *HANDA (1972)*. This doubling most probably results from the preferential removal of calcium by precipitation as carbonate. Using a simple thermodynamic approach (*GARRELS and CHRIST, 1965*), we have calculated the degree of calcite saturation in these waters. The results of these calculations show that (Fig. 8), by and large, the highland waters are undersaturated with respect to calcite in

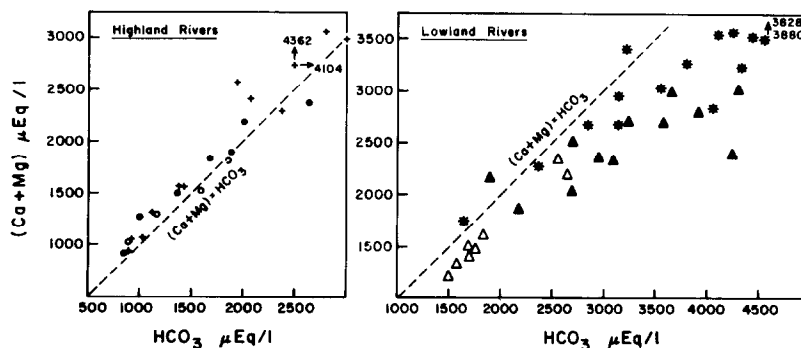


FIG. 6. Scatter diagram of $(\text{Ca} + \text{Mg})$ and HCO_3 for the highland and lowland rivers. In the highland waters, HCO_3 nearly balances $(\text{Ca} + \text{Mg})$, a result expected for carbonate weathering. In lowland rivers, HCO_3 is in excess of $(\text{Ca} + \text{Mg})$, which requires alkalis to balance the charge.

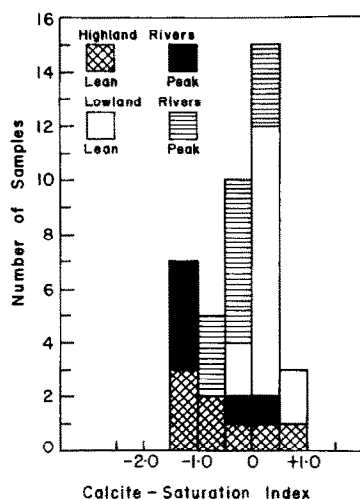


FIG. 8. Degree of calcite saturation in the highland and lowland river during their lean and peak flow conditions. During the lean flow, the lowland waters are supersaturated with respect to calcite.

contrast to the lowland rivers, which are just at, or slightly above, saturation level. A closer look at the lowland rivers' data (Fig. 8) further indicates that calcite supersaturation is more common during their lean flow. The supply of subsurface waters rich in total alkalinity and subsequent loss of CO_2 can account for the slight supersaturation. The evaporation during summer months in these semi-arid regions, coupled with the slight supersaturation of calcite, can aid the precipitation of carbonate, required to account for the high Mg:Ca ratio observed during the lean flow period.

III. Clay mineralogy of river sediments and silicate weathering in the Ganga-Brahmaputra basins. The role of silicate weathering in the solution chemistry of these rivers can also be evaluated based on a simple thermodynamic approach. This is a difficult exercise since from any given terrain many silicate weathering reactions occur simultaneously, and water chemistry by itself cannot provide an unambiguous identity to these reactions. However, we attempt to constrain the possible reactions based on the concentrations of dissolved silica (which is derived solely from silicate weathering), sodium, potassium and data on the mineralogy of the river sediments.

The clay mineral composition of the sediments (Table 3) collected near the source waters (of the Ganga and its northern tributaries) is dominated by illite (75–80%). Kaolinite and chlorite constitute the remaining 20% of the clays (*cf.* NAIDU *et al.*, 1985). Smectite is not detectable in these sediments. The Yamuna and the Brahmaputra, near their source, also show an illite-dominated mineralogy (Table 3). In marked contrast, smectite is the most abundant clay mineral in the lowland rivers, the Chambal, Betwa and Ken. The difference in the clay mineral abundances between the Himalayan rivers (sampled near their source) and the lowland rivers can be understood in terms of their regional geology (Fig. 1). The watersheds of the highland rivers consist essentially of acidic rocks, whereas the Chambal, the Betwa and the Ken originate in the Deccan Traps and flow through basic effusives. The clay mineralogy of sediments in the Ganga main channel is

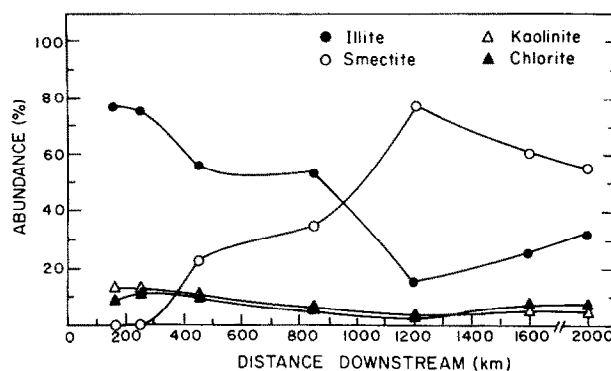


FIG. 9. Downstream variations in the abundances of clay minerals in the sediments along the Ganga. The variation seems to be controlled by the mixing of the highland and lowland tributaries.

controlled by the mixing of the tributaries (Fig. 9). For example, after the confluence with the Yamuna, the Ganga sediments are enriched in smectite (Table 3, Fig. 9).

In both the highland and lowland rivers there is a definite excess of sodium over chloride (Fig. 10). This excess (Na^+ ; STALLARD and EDMOND, 1983) is attributable to silicate weathering. The $(\text{Na}^+ + \text{K})/\text{TZ}^+$ ratio is an index to assess the contribution of cations *via* silicate weathering (STALLARD and EDMOND, 1983, 1987). This ratio for the highland rivers ranges between 0.05 and 0.15 (mean = 0.1), without any discernable seasonal trend (Fig. 4). The low $(\text{Na}^+ + \text{K})/\text{TZ}^+$ indicates that there is no pronounced contribution of cations to the highland rivers from the degradation of aluminosilicates. This reinforces our earlier inference based on $(\text{Ca} + \text{Mg})$ abundance and $(\text{Ca} + \text{Mg})/\text{HCO}_3^-$ ratio that carbonate weathering is the major source of cations to the highland waters. In the lowland rivers, the contribution of alkalis to the cation balance is relatively more pronounced (Fig. 4). In these waters, the $(\text{Na}^+ + \text{K})/\text{TZ}^+$ range between 0.1 and 0.42 (mean = 0.2), the ratio being relatively higher during the lean

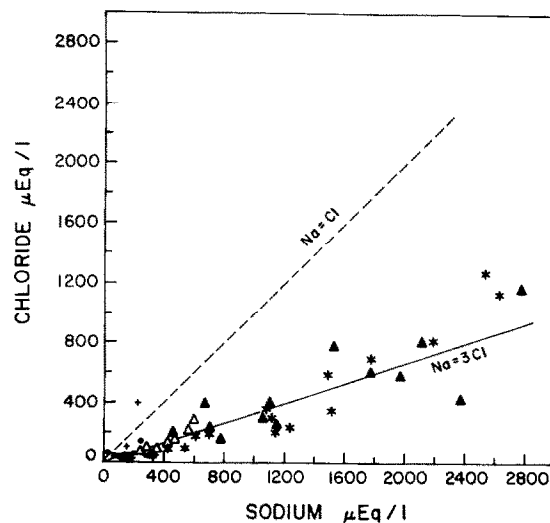


FIG. 10. Scatter diagram of Na vs. Cl. The Na:Cl equivalent ratio in the samples scatters around ~ 3 .

flow. The $(\text{Na}^* + \text{K})/\text{TZ}^+$ value of ~ 0.2 leads us to infer that the contribution of cations *via* silicate weathering is more significant in these rivers. However, this inference would be unrealistic if the supply of alkalis to these waters from dissolution of soil salts and saline groundwaters is significant. This would make estimates of cations supplied *via* silicate weathering, based on $(\text{Na}^* + \text{K})/\text{TZ}^+$, upper limits.

Another parameter which can provide some insight into silicate weathering processes is $\text{Si}/(\text{Na}^* + \text{K})$. This ratio is ~ 1 for the highland waters and ~ 0.3 for the lowland rivers. There can be different silicate weathering reactions and their combinations, which can result in the above $\text{Si}/(\text{Na}^* + \text{K})$ ratios (STALLARD, 1980); for example, reactions involving weathering of feldspars and micaceous minerals to kaolinite and the formation of smectite can yield such observed ratios. However, in these waters, the influence of saline/alkaline soils on the $(\text{Na} + \text{K})$ abundances and the role of algal productivity on Si concentrations constrains the application of $\text{Si}/(\text{Na}^* + \text{K})$ as an index of silicate weathering.

From the measured pH, Na, K, Ca, and Si concentrations, we can also attempt to establish, using a thermodynamic approach, the clay mineral assemblages which would be consistent with the water chemistry. When the chemical composition of the Ganga and its tributaries are plotted on log activity diagrams of $\text{K}/\text{H-H}_4\text{SiO}_4$ (GARRELS and CHRIST, 1965; STALLARD, 1980), most of the data points fall in the kaolinite field. This is not quite consistent with the clay mineral composition of the sediments, which shows that kaolinite is only a minor constituent. Such an inconsistency between the water chemistry and clay mineral data can arise because of (i) lack of proper chemical equilibrium between solution and solid phases, (ii) slight uncertainties in the free energies of the minerals, which could drastically shift the boundaries between the various mineral phases and (iii) nonconservative behaviour of silica in the waters, resulting from its biological removal. Indeed, by using a slightly different set of free energy data for the potassium minerals (DREVER, 1982), we find better consistency between water chemistry and clay mineralogy for the highland rivers.

Based on the discussions presented in the preceding section, we conclude that the chemistry of highland waters is dominated by carbonate weathering. In the lowland waters, the presence of bicarbonate excess over $(\text{Ca} + \text{Mg})$, the relatively high $(\text{Na}^* + \text{K})/\text{TZ}^+$ and the high abundance of smectite in the sediments seem to indicate that the supply of cations to these waters by silicate weathering is more significant than in the highland waters.

Fluxes of dissolved major ions via Ganga and Brahmaputra Rivers

A knowledge of the elemental fluxes *via* rivers is essential to understanding the marine geochemical cycles of elements. In this section, we present the average annual fluxes of dissolved major ions transported by the Ganga (and its tributaries) and Brahmaputra rivers. Data on the water discharge of these rivers at the time of sampling could not be obtained, because of logistic and other regulatory problems. Therefore, we have used the discharge data compiled by UNESCO (1971) and RAO (1975) for flux calculations. The seasonal variation in the water discharge has been discussed in the Geohydrology section above.

The discharge-weighted average major ion composition of the Ganga (at Patna), Yamuna (at Allahabad) and Brahmaputra (at Goalpara) are given in Table 5. For calculating the mean composition of the Ganga (at Patna) and the Yamuna (at Allahabad), it was assumed that the seasonal variation in their discharge follows the same pattern as that of the Ganga at Farakka (USESCO, 1971). The average composition given in Table 5 differs slightly from our earlier published values (SARIN, 1983; SARIN and KRISHNASWAMI, 1984) because of the inclusion of November 1983 data and differences in weighting factors. The composition of the Ganga waters at Patna (Table 5), when compared with the discharge-weighted average at Rajmahal (downstream Patna, recalculated from HANDA, 1972), shows that the concentrations of K, Ca and SO_4 during 1968 and 1969 (HANDA's, 1972, data) and 1982 and 1983 (results of this work, Table 5) are quite the same. For Na, Mg and Cl the 1982 to 1983 concentrations are about 40 to 110% higher than those measured in 1968 to 1969. It is difficult to ascribe any particular reason for the observed discrepancy. It could be due to one or a combination of the following: (i) natural variations in the composition from year to year, (ii) sampling artifact arising from differences in the frequency of analysis, (iii) an increase in salinity of surface soil, resulting from the enhanced use of groundwaters in recent years for irrigation in the drainage basin and (iv) anthropogenic effects. The average composition of the Ganga and Brahmaputra waters has also been given by SUBRAMANIAN (1985). However, his results show a significant excess of TZ^+ over TZ^- ; about 60% for the Ganga and a factor of ~ 2 for the Brahmaputra. Because of this charge imbalance, we have refrained from comparing his data with our results.

For comparison, Table 5 also lists recent data on the major ion composition of some of the other large river systems,

TABLE 5 MAJOR ION COMPOSITION OF SELECTED WORLD RIVERS

River	Na	K	Mg	Ca	HCO_3^-	Cl	SO_4	SiO_2	TDS	Reference
	(μmole.l ⁻¹)								(mg.l ⁻¹)	
Yamuna	860	61	275	595	2131	353	106	171	216	This work
Ganga(1)	438	68	288	634	2084	140	89	137	178	"
Brahmaputra(2)	92	48	157	351	957	31	106	130	100	"
Indus	391	51	230	660	1469	200	275	85	171	Meybeck (1979)
Mekong	157	51	132	355	949	149	40	147	99	"
Chiang	179	32	269	1120	2420	116	186	96	213	Hu et al (1982)
Amazon	80	25	42	136	340	36	22	15	41	"
Zaire	60	27	47	52	197	28	12	144	29	"
World Average	191	38	166	398	1019	105	96	207	115	"

(1) Ganga at Patna

(2) Brahmaputra at Goalpara

TABLE 6. FLUXES OF MAJOR IONS AND CHEMICAL DENUDATION RATES OF SELECTED WORLD RIVERS

River	Discharge (10^{12} l.yr $^{-1}$)	Area (10^3 km 2)	Na	K	Mg	Ca	HCO $_3$	Cl	SO $_4$	SiO $_2$	TDS*	CDR**
(10 9 moles.yr $^{-1}$)												
Yamuna	93	140	80	6	26	55	198	33	10	16	20	143
Ganga	393#	975\$	172	27	113	249	819	55	35	54	70	72
Brahmaputra	609\$	580\$	56	29	96	214	583	19	64	79	61	105
Indus	238	970	93	12	55	157	350	48	65	20	41	42
Mekong	577	795	91	29	76	204	547	86	23	85	57	72
Chiang	1063	1960	190	34	286	1190	2570	123	198	102	226	116
Amazon	5500	6300	440	140	230	750	1870	200	120	83	223	35
Zaire	1230	4104	74	33	58	64	242	34	15	177	36	9
World Average	31400	101000	6000	1200	5200	12500	32000	3300	3000	6500	3600	36

\$ Meybeck 1979 # Ganga at Farakka (12 year average, UNESCO 1971)

* Million Tons.yr $^{-1}$ ** CDR = Chemical Denudation Rate (Tons.km $^{-2}$.yr $^{-1}$)

including a few major Himalayan rivers. These data show that the Yamuna (at Allahabad), the Ganga (at Patna) and the Indus all have similar salinity and that their salinities are comparable to that of Chiang Jiang (HU *et al.*, 1982). The high concentration of sodium and chloride in both the Yamuna and Ganga rivers is mainly due to contribution from soil salts. The Brahmaputra (at Goalpara) and the Mekong contain about a factor of two less saline than the other Himalayan rivers. The composition of the Brahmaputra by and large resembles that of the global average river water (Table 5).

The flux of dissolved material transported by the Ganga and Brahmaputra rivers is given in Table 6. The major ion chemistry of the Ganga at Patna (November 1983) is very similar to that at Aricha Ghat before its confluence with Brahmaputra (Table 2, Fig. 2). Similarly, the chemistry of the Brahmaputra at Goalpara (December 1982) closely resembles the sample collected at Aricha Ghat during the same season (November 1983, Table 2). These observations allow us to assume that the average major ion composition of the Ganga and the Brahmaputra (Table 5) is representative of these rivers before their outfall into the Bay of Bengal.

Among the rivers studied in this work, the Ganga transports the most dissolved solids to the ocean: 70 million tons per year. A comparison of the major ion fluxes transported by the Ganga and the Chiang Jiang shows that they transport nearly equal quantities of Na and K to the oceans, although the Ganga's water discharge is only about 37% of that of the Chiang Jiang (HU *et al.*, 1982, Table 6). Also, the flux data of the Ganga and the Brahmaputra show that, although the water discharge of the Ganga is only about 65% of that of the Brahmaputra, it carries about 15% more salts to the sea. The Ganga carries substantially more sodium, bicarbonate and chloride than the Brahmaputra. It ranks close to Chiang Jiang in the transport of sodium. Although the Ganga supplies about 40% of the Na, Mg, HCO $_3$ and SiO $_2$ as that of the Amazon, its discharge is only about 7% of it.

On a global scale, the Ganga and the Brahmaputra rivers together account for about 3% of the total flux of dissolved major ions to the oceans *via* rivers, quite similar to their contribution to the global water discharge. Together, these two rivers annually supply ~ 130 million tons of dissolved salts to the Bay of Bengal, of which ~ 70 million tons comes from the Ganga. The chemical denudation rates for the Ganga and the Brahmaputra basins are ~ 72 and ~ 105 tons km $^{-2}$

yr $^{-1}$, respectively. The chemical denudation rates of the Ganga and the Mekong are nearly the same, probably because of their similar climatic and topographic features. The denudation rates of the Ganga and the Brahmaputra are about a factor of 2 to 3 higher than the global average rate of ~ 36 tons km $^{-2}$ yr $^{-1}$ (HU *et al.*, 1982). Such high rates for the Himalayan rivers, particularly for the Brahmaputra, probably result from the high relief and heavy rainfall (MEYBECK and CARBONNEL, 1975).

SUMMARY AND CONCLUSIONS

This study provides significant information on the geochemical processes controlling the major ion chemistry of the Ganga and Brahmaputra river waters and their fluxes to the Bay of Bengal. The following conclusions result from this study:

I) The Ganga and the Brahmaputra together account for $\sim 3\%$ of dissolved materials discharged into the world's oceans *via* rivers. The annual flux of dissolved materials transported by these rivers to the Bay of Bengal is ~ 130 million tons. On an average, the Ganga (at Patna) and the Brahmaputra (at Goalpara) contain, respectively, about 178 and 100 mg $\cdot$ l $^{-1}$ dissolved salts. The chemical denudation rates for both these rivers are factors of 2 to 3 higher than the global average, resulting from the high relief and rainfall.

II) The Himalayan rivers (the Ganga, Yamuna and Brahmaputra, near their sources, and the Gandak and Ghaghara) all have water chemistries dominated by carbonate weathering. In these waters (Ca + Mg) and HCO $_3$ account for most of the ions. The chemistry of the lowland waters (the Chambal, the Betwa, the Ken and the Son) suggests that contributions of major ions to these waters from silicate weathering and saline and alkaline soils/groundwaters are relatively more pronounced.

Acknowledgements—We are grateful to N. Hussain, P. Sharma and J. P. Bhavsar for their help during sampling expeditions. We thank R. Ramesh and R. Rengarajan for help in computer work and K. R. Nambiar for his able assistance in typing the manuscript. The financial support for this study was provided in part by grants from PL-480, Departments of Science & Technology (DST) and Ocean Development (DOD) to PRL, and by NSF grants INT-8117218 and INT-8218484 to WSM. We thank J. D. Milliman, M. Meybeck and an anonymous reviewer for their critical reviews.

Editorial handling: S. E. Calvert

REFERENCES

- ABBAS N. and SUBRAMANIAN V. (1984) Erosion and sediment transport in the Ganges River Basin (India). *J. Hydrol.* **69**, 173–182.
- Analytical Methods Manual*, Environment Canada (1979). Inland Waters Directorate, Ottawa.
- BHARGAVA G. P. and BHATTACHARJEE J. C. (1982) Morphology, genesis and classification of salt affected soils. In *Rev. Soil Res. Ind. Part II*, pp 508–528. The Indian Society of Soil Science.
- BHARGAVA G. P., PAL D. K., KAPOOR B. S. and GOSWAMI S. C. (1981) Characteristics and genesis of some sodic soils in the Indo-Gangetic alluvial plains of Haryana and Uttar Pradesh. *J. Ind. Soc. Soil Sci.* **29**, 61–70.
- BISCAYE P. E. (1965), Mineralogy and sedimentation of recent deep-sea clay in the Atlantic Ocean and adjacent seas and oceans. *Geol. Soc. Amer. Bull.* **76**, 803–832.
- CARBONNEL J. P. and MEYBECK M. (1975) Quality variations of the Mekong river at Pnom Penh, Cambodia, and chemical transport in the Mekong Basin. *J. Hydrol.* **27**, 249–265.
- CSSRI (1975) *Map of India, Salt Affected Soils*. Central Soil Salinity Research Institute, Karnal, India.
- CWPC (1973) Report on chemical investigation of river waters of India, March 1973. Central Water and Power Commission, Govt. of India.
- DREVER J. I. (1982) *The Geochemistry of Natural Waters*. Prentice-Hall, 388p.
- FLORENCE T. M. and FARRAR Y. J. (1971) Spectrophotometric determination of chloride at the parts-per-billion level by mercury (II) thiocyanate method. *Anal. Chim. Acta*, **54**, 373–378.
- GANNISER A. (1964) *Geology of the Himalayas*. Interscience, London, 289p.
- GARRELS R. M. and CHRIST C. L. (1965) *Solutions, Minerals and Equilibria*, Harper & Row, 450p.
- GARRELS R. M. and MACKENZIE F. T. (1971) *Evolution of Sedimentary Rocks*, W. W. Norton, 397p.
- GIBBS R. J. (1972) Water chemistry of the Amazon River. *Geochim. Cosmochim. Acta*, **36**, 1061–1066.
- HANDA B. K. (1968). Chemical composition of rain water in some parts of North India. *Ind. J. Met. Geophys.*, **19**, 175–180.
- HANDA B. K. (1972) Geochemistry of the Ganga River Water. *Ind. Geohydrol.* **2**, 71–78.
- HANDA B. K. (1978) Technical report No. 7 on the hydrogeochemistry of the Brahmaputra River. *Hydrol. Rev.* **4**, 99–105.
- HOLEMAN J. N. (1968) Sediment yield of major rivers of the world. *Water Resource Res.* **4**, 737–747.
- HOLLAND H. D. (1978) *The Chemistry of the Atmosphere and Oceans* J. Wiley & Sons, 351p.
- HU M., STALLARD R. F. and EDMOND J. M. (1982) Major ion chemistry of some large Chinese Rivers. *Nature*, **298**, 550–553.
- Hydrology Review* (1976) Discharge of selected rivers of India. CSIR, New Delhi **2**, 8–12.
- MATTER A. (1974) Burial diagenesis of pelitic and carbonate deep-sea sediments from the Arabian sea. In *Init. Repts. DSDP* (eds. S. B. WHITMARSH and O. E. WESER), Vol. 23.
- MEYBECK M. (1979) Concentrations des eaux fluviales en éléments majeurs et apports en solution aux océans. *Rev. Geol. Dynam. Geogr. Phys.* **21**, 215–246.
- MEYBECK M. and CARBONNEL J. P. (1975) Chemical transport by the Mekong River. *Nature*, **255**, 134–136.
- MILLIMAN, J. D. and MEADE, R. H. (1983) World-wide delivery of river sediment to the oceans. *J. Geol.* **21**, 1–21.
- NAIDU A. S., MOWATT T. C., SOMAYAJULU B. L. K. and RAO K. S. (1985) Characteristics of clay minerals in the bed loads of major rivers of India. In *Proc. 3rd Intl. Wkshop on Transport of Carbon and Minerals in Major Rivers*, pp. 559–568. SCOPE/ UNEP, Hamburg.
- Perkin-Elmer Handbook* (1976) Analytical methods for AAS. Perkin-Elmer, CT, U.S.A.
- RAO K. L. (1975) *India's Water Wealth*. Orient Longman Ltd., New Delhi, 255p.
- RAYMAHASHAY B. C. (1973) Characteristics of stream erosion in the Himalayan region of India. *Proc. 1st Symp. Hydrogeochem. Biogeochem.*, Tokyo, pp. 82–92. Clarke Co. Washington, D.C.
- REEDER S. W., HITCHON B. and LEVINSON A. A. (1972) Hydrogeochemistry of the surface waters of the Mackenzie River drainage basin, Canada—I. Factors controlling inorganic composition. *Geochim. Cosmochim. Acta*, **36**, 181–192.
- SARIN M. M. (1983) Chemistry of major elements and uranium—Thorium series nuclides in Indian rivers. Ph.D. thesis, Gujarat University, India.
- SARIN M. M. and KRISHNASWAMI S. (1984) Major ion chemistry of the Ganga-Brahmaputra river systems, India. *Nature*, **312**, 538–541.
- SEQUEIRA R. and KELKAR D. (1978) Chemical composition of monsoonal rain water over India. *J. Appl. Met.* **17**, 7–18.
- STALLARD R. F. (1980) Major element geochemistry of the Amazon River system. Ph.D. thesis, Massachusetts Institute of Technology.
- STALLARD R. F. and EDMOND J. M. (1981) Geochemistry of the Amazon, precipitation chemistry and the marine contribution to the dissolved load at the time of peak discharge. *J. Geophys. Res.* **86**, 9844–9855.
- STALLARD R. F. and EDMOND J. M. (1983) Geochemistry of the Amazon, the influence of geology and weathering environment on the dissolved load. *J. Geophys. Res.* **88**, 9671–9688.
- STALLARD R. F. and EDMOND J. M. (1987) Geochemistry of the Amazon, weathering chemistry and limits to dissolved inputs. *J. Geophys. Res.* **92**, 8293–8302.
- STRICKLAND J. D. H. and PARSONS T. R. (1972) *A Practical Handbook of Sea Water Analysis*. Fisheries Research Board of Canada, Ottawa, 310p.
- SUBRAMANIAN V. (1979) Chemical and suspended sediment characteristics of rivers of India. *J. Hydrol.* **44**, 37–55.
- SUBRAMANIAN V. (1985) Geochemistry of river basins in the Indian subcontinent. Part I. Water chemistry, chemical erosion and water-mineral equilibria. *Mitt. Geol.—Palont. Inst. Univ. Hamburg*, **58**, 495–511.
- UNESCO (1971) *Discharge of Selected Rivers of the World, Vol. II. Monthly and Annual Discharges Recorded at Various Selected Stations*, 194p.
- VALDIYA K. S. (1980) *Geology of Kumaun Lesser Himalayas*, Wadia Inst. of Himalayan Geology, Dehra Dun, 291p.
- WADIA D. N. (1981) *Geology of India*. Tata McGraw-Hill, New Delhi, 508p.