Chapter-5

Sediment Geochemistry of the Ganga River: Implications for silicate erosion fluxes.

5.1 Introduction

This chapter presents the results on the major element composition including inorganic and organic carbon in sediments (bank, suspended and <4µm fraction) of the Ganga river and its tributaries. The goal of these measurements, as discussed in chapter-1, is to explore their use to learn about the intensity of chemical and silicate weathering in the basin and the mobility of Na, K, Mg, Ca and Sr from particulate to dissolved phase. Further, particulate organic carbon measurements provide data on the flux of organic carbon transported by the Ganga to the Bay of Bengal and its significance in contributing to sequestration of carbon from the atmosphere.

Commonly, contemporary silicate erosion rates are derived, as mentioned earlier, by modelling dissolved major ion composition of rivers. These models are generally based on the use of chloride corrected Na (or dissolved SiO_2) in rivers as a proxy of silicate weathering (Edmond and Huh, 1997; Gaillardet et al., 1999; Galy and France-Lanord, 1999; Krishnaswami et al., 1999; Dalai et al., 2002; Bickle et al., 2005; Singh et al., 2005). These efforts have yielded useful results on present day silicate erosion rates and associated CO_2 consumption for many Himalayan basins. These rates derived from dissolved phase data however, can be prone to uncertainties resulting from challenges to the assumptions of the model and the large range in the various end member elemental ratios (Ca/Na), (Mg/Na) used in them. One example is the validity of the use of chloride corrected Na as a proxy of silicate weathering. It was shown in chapter-4 that contribution of Na from saline soils present in the Ganga plain can affect the estimates of silicate erosion rates. Similarly, anthropogenic input of major ions to rivers can be another source of uncertainty. To check on this, as well as to obtain independent estimate of silicate erosion rate, other repositories which preserve such information have to be explored. One such repository is river suspended matter. Under steady state conditions the amount of fresh rock eroded per unit time in a river basin is balanced by the flux of dissolved and particulate phases (Martin and Meybeck., 1979; McLennan, 1997; Stallard, 1995; Roy et al., 1999;

Gaillardet et al., 1995; Canfield, 1997; Das and Krishnaswami, 2007). Therefore by comparing the chemical composition of source rocks with that of river suspended phase it should be possible to calculate silicate erosion rates. Recently a few studies (Dupre et al., 1996; Gaillardet et al., 1997; Louvat and Allegre, 1997; Picouet et al., 2002; Vigier et al., 2005; Gislason et al., 2006: Das and Krishnaswami, 2007) have utilized the chemical composition of both river water and sediments to constrain the erosion fluxes.

The application of sediment composition to determine silicate erosion rates depends on the knowledge of representative composition of both parents rocks and river suspended matter. In the Himalaya, despite its diverse lithology, representative chemical composition of source rocks supplying suspended matter to the Ganga basin can be obtained. It has been shown in chapter-3, based on Sr and Nd isotopes, that the sediments of the Ganga basin in the plain are predominantly from the Higher Himalaya, specifically HHC. Therefore, as a first approximation, the major element composition of HHC can be used as representative of the rocks supplying suspended sediments to the Bay of Bengal. Alternatively, as will be discussed in the subsequent section, the chemistry of bank sediments can also serve as an approximation of parent rock composition.

In this study, attempts to determine silicate erosion in the Ganga basin has been made through studies of major element abundances in bank sediments and suspended matter of the Ganga and its major tributaries. The results are compared with that obtained form the dissolved phase data. The major objectives of this study are to (i) determine the chemical composition of river sediments from the Ganga basin, including their carbonate and organic carbon contents (ii) assess the mobility of selected major elements from parent rock during chemical erosion and calculate their erosion fluxes to the Bay of Bengal (iii) estimate silicate erosion rates and associated CO_2 consumption from suspended sediment data and compare the results with those derived from dissolved phase data.

Table-5.1: Major element composition in bank sediments from Ganga river and its tributaries

Sample	River	Location	Date	Ca	Mg	Na	K	Fe	Al	IC	C_{org}	P	Sr*
			d/m/y	wt (%)								$\mu g\ g^{-1}$	
Ganga Mainstream													
RS03-2	Bhagirathi	Gangotri	02.0503	0.6	0.4	2.5	2.8	1.5	7.3	0	0.14	696	61
RS03-3	Bhagirathi	Gangotri	02.05.03	0.6	0.3	2.4	2.6	1.1	6.3	0	0	558	58
RS03-7	Bhagirathi	Uttarkashi	03.05.03	0.8	0.3	1.1	1.9	2.9	3.9	0.05	0.16	730	95
RS03-1	Ganga	Rishikesh	01.05.03	1.6	0.9	1.2	1.9	2	5.1	0.53	0.19	431	78
BR352	Ganga	Allahabad	14.05.04	0.9	0.7	1.3	1.8	1.8	4.2	0.2	0.12	360	138
BR06-12-2	Ganga	Allahabad	20.10.06	1	0.6	1	1.3	1.3	3.3	0.09	0.03		64
BR351 (<4μm)	Ganga	Allahabad	14.05.05	2	3	0.4	3.8	12.7	12	0.77	0.72		38
BR06-SL12	Ganga	Allahabad	20.10.06	1.5	1.7	0.8	2.3	3.7	6	0.31	2.2		
BR382	Ganga	Varanasi	17.05.04	1.3	0.5	1.1	1.4	1.6	3.5	0.22	0.09	448	69
BR06-14-2	Ganga	Varanasi	21.1006	2.5	0.6	0.7	1.1	2.6	3.2	0.12	0.04		63
BR383 (<4μm)	Ganga	Varanasi	17.05.05	1.8	2.1	0.2	2.9	7.8	11.6	0.33	0.96		44
BR06-SL14	Ganga	Varanasi	21.10.06	2.7	1.9	1.1	1.6	4.9	6.4				
BR06-10-1	Ganga	Ghazipur	19.10.06	1.1	0.5	0.9	1.5	1.2	3.2	0.01	0.15		67
BR06-SL10	Ganga	Ghazipur	19.10.06	3.6	1.7	0.5	1.6	4.9	6.5	0.75	1.81		
BR06-802	Ganga	Doriganj	19.10.06	2.8	0.8	0.8	1.3	1.9	3.2	0.75	0.09		67
BR06-SL8	Ganga	Doriganj	19.10.06	3.9	2	0.7	2.7	4.1	7.5	1.17	0.66		63
BR306	Ganga	Patna	07.0504	2.3	0.8	1.1	1.5	2.2	3.9	0.65	0.02	682	74
BR06-303	Ganga	Patna	16.10.06	2.4	0.8	0.8	1.4	1.7	3.4	0.57	0.06		75
BR06-SL3	Ganga	Patna	16.10.06	3.2	1.6	0.6	2.3	4.5	7.4	0.84	1.11		66
BR315	Ganga	Barauni	08.05.04	3.8	0.9	1.2	1.7	1.9	4.1	1.04	0.14	470	90
BR06-404	Ganga	Barauni	17.10.06	3.3	0.7	0.8	1.3	1.5	3.4	0.89	0.09		82
BR314 (<4μm)	Ganga	Barauni	08.05.05	3.8	2.4	0.3	3.1	7.4	11				45
BR06-SL4	Ganga	Barauni	17.10.06	4.4	1.7	0.7	2.5	4.2	7.8	1.22	0.83		67
BR324	Ganga	Rajmahal	09.05.04	3.3	1.1	1.2	1.8	2.5	5	0.82	0.13	605	92
BR06-101	Ganga	Rajmahal	15.10.06	2.9	1	1	1.8	2.2	4.2	0.73	0.15		102
BR06-SL1	Ganga	Rajmahal	15.10.06	1.3	1.6	0.7	2.9	4.5	8.1	0.23	0.64		75
BR325(<4μm)	Ganga	Rajmahal	09.05.05	2.1	2.2	0.2	2.9	8.2	12.4				41

Alaknanda													
RS03-28	Alaknanda	Birhai, B.Confl	05.05.03	2.3	1.1	1.3	2	2.5	5.1	0.76	0.26	612	84
RS03-27	Birahi Ganga			10.1	7.5	0.5	1	2.1	2.7	5.61	0.06	329	48
RS03-29	Birahi Ganga	Birahi	05.05.03	12.4	8.6	0.5	0.9	1.4	2	7.23	1.88	192	44
RS03-31	Pindar	Pindar Valley	05.05.03	4.3	1.3	1.1	1.3	2.3	4	1.21	0.08	635	117
Bhagirathi Tributaries													
RS03-9	Syansu Gad		03.05.03	0.2	0.6	0.9	2	3.1	5.7	0.04	0.09	403	37
RS03-12	Bhilangna	Ghanshyali	03.05.03	1.6	0.8	1.3	2	4.2	5.6	0.1	1.61	470	69
Tributaries in Plain													
BR348	Yamuna	Allahabad	15.05.04	2.1	0.4	1.1	1.5	1.6	3.4	0.5	0.12	325	101
BR06-13-2	Yamuna	Allahabad	20.10.06	1	0.5	1	1.3	1.3	3.1	0.4	0.06		88
BR06-SL13	Yamuna	Allahabad	20.10.06	6.3	2.3	1.6	1.5	5.3	6.7				
BR378	Gomti	Ghazipur	16.05. 04	1.5	0.5	1.1	1.9	1.4	4.1	0.34	0.16	425	81
BR06-11-3	Gomti	Ghazipur	19.10.06	1.1	0.4	1	1.5	1.1	3.2	0.08	0.05		73
BR06-SL11	Gomti	Ghazipur	19.10.06	2.8	2.3	0.8	2.8	4.7	7.5	0.71	1.98		
BR365	Rapti	Gorakhpur	15.05.04	1.8	0.4	0.6	1.2	1.4	2.7	0.55	0.14	355	37
BR364 (<4µm)	Rapti	Gorakhpur	15.05.05	2	1.9	0.2	3.8	7.4	12.4				41
BR355	Ghaghra	Ayodhya	15.05.04	2.6	0.9	1	1.5	1.6	3.5	0.91	0.18	379	67
BR356 (<4µm)	Ghaghra	Ayodhya	15.05.05	2.9	2.8	0.3	3.9	7.2	11.7				37
BR371	Ghaghra	Doharighat	15.05.04	2.8	1	0.9	1.5	1.1	3.7	0.99	*0.19*	502	76
BR372 (<4µm)	Ghaghra	Doharighat	15.05.05	2.7	2.5	0.3	3.8	7.5	11.8				41
BR343	Ghaghra	Revelganj	12.05.04	2.6	0.9	0.9	1.7	2.1	3.9	0.91	0.17	410	80
BR06-905	Ghaghra	Revilganj	19.10.06	2.7	0.8	0.8	1.4	1.2	3.1	0.81	0.06		66
BR344 (<4µm)	Ghaghra	Revelganj	12.05.05	3.2	2.3	0.4	3.7	6.5	10.9	1.04	1.06		50
BR06-SL9	Ghaghra	Revilganj	19.10.06	4.1	2.1	0.6	3	4.4	8	1.23	0.76		60
BR336	Gandak	Barauli	11.05.04	4.6	1	1.2	1.9	2.2	4.5	1.41	0.26	518	105
BR335 (<4µm)	Gandak	Barauli	11.05.05										64
BR310	Gandak	Hajipur	07.05.04	6	1.1	1.2	1.7	2.2	4.2	1.72	0.25	664	109
BR06-701	Gandak	Hazipur	18.10.06	5.8	1.1	0.9	1.5	2	4	1.64	0.1		108
BR06-SL7	Gandak	Hazipur	18.10.06	6.2	1.8	0.8	2.8	3.8	7.6	1.85	0.63		86

BR330	Kosi	Dumarighat	10.05.04	0.7	0.4	1.4	2	1.8	4.8	0.03	*0.05*	377	79
BR331	Kosi	Dumarighat	10.05.04	1.1	1	0.9	3.1	3.8	5.9	0.31	0.2	621	
BR331(<4μm)	Kosi	Dumarighat	10.05.05	0.9	1.9	0.3	3.6	8.5	13.2				33
BR06-502	Kosi	Dumarighat	18.10.06	1.1	0.7	1.2	1.8	1.8	4.3	0.05	0.07		90
BR06-SL5	Kosi	Dumarighat	18.10.06	0.9	1.6	0.9	3.4	4.4	9.1	0.07	0.47		71
BR06-603	Baghmati	Dumarighat	18.10.06	1.6	1.1	1	2.3	3	5.5	0.25	0.17		81
BR06-SL6	Baghmati	Dumarighat	18.10.06	1.2	1.4	0.8	3	4.4	8.3	0.15	0.51		93
BR06-205	Son	Koilawar	16.10.06	0.5	0.2	0.4	1.9	0.6	2.2	0	0.02		65
BR06-SL2	Son	Koilawar	16.10.06	1.7	1.2	0.7	1.7	5.6	9.4	0.17	1.77		

Analyses carried out on total bank sediments, their <4μm size fraction and suspended samples except for Sr which is in silicate fraction (Chapter-3).

5.2 Results and discussion

This work is based on the elemental geochemistry of the bed/bank sediments and suspended matter collected from different locations in the Ganga river system (Figs-2.1a &b). These sediments were analysed for Na, K, Ca, Mg, Al, Fe, inorganic and organic C concentrations. The analytical methods are discussed in chapter-2, section 2.5.2. In addition to these samples, analyses were also made in the < 4μm fractions of bank sediments; this fraction was separated from total sediments by the settling. The results are presented in Table-5.1.

5.2.1 Major element geochemistry and relative mobility of elements in the Ganga river system:

The chemical composition of the Ganga sediments shows significant variability along the course of the river. The major element Na, Fe and Al, abundances in the bank sediments vary over a factor of ~ 3. The Ca and Mg concentrations in the samples are derived from both silicates and carbonates. Therefore, to estimate the Ca and Mg in the silicates, appropriate correction for their contribution from carbonate has to be made. This was done by leaching the bank sediments with 0.6 N HCl (section-5.3) and measuring Ca and Mg in the acid leaches. It is assumed that the Ca and Mg in the acid leach are only from carbonates. This exercise was carried out for samples of May 2004. For October 2006 samples and <4μm fraction of bank sediments, it was calculated from the measured inorganic carbon content (section-5.3) and Ca/Mg ratio of 2004 samples from the same location. Sr, as mentioned in chapters-2 and 3 was measured in silicate fraction of the sediments. Mineralogical composition of sediments, particularly the abundance of quartz (and carbonates) relative to other silicate minerals determines the concentrations of the above elements in sediments. Size sorting during transportation and deposition is an important process regulating the mineralogical composition and hence the chemical composition of sediments. Some of the variability in the concentrations of various elements observed in this study can result from this process. Fig-5.1 are plots of Na, K and Fe vs Al in the bank sediments, their <4μm fraction and in suspended load of all the rivers sampled. The data show significant positive correlation between Na-Al, K-Al and Fe-Al in the bank sediments samples, bringing out the effect of dilution of silicate minerals containing Na, K, Fe and Al with quartz (and carbonates). As these diluents do not contain Al, Na, K and Fe, their mixing will result only in decreasing the concentration of these elements in the bulk samples without affecting their ratio with Al. Apart from silicates, Ca, Mg and Sr are also sourced from carbonates therefore their abundances have been corrected to get silicate derived component Ca_{sil} , Sr_{sil} and Mg_{sil}. These data are also plotted vs-Al in Fig-5.1. The figure shows that among these three alkaline earths, there is a good correlation only for Mg_{sil} with Al in the bank sediments indicating the relatively conservative behaviour of Mg in these samples. The positive correlation is also an indication that the bank sediments have not been subjected to significant chemical weathering, consistent with CIA values as discussed in the next section (5.3). Table-5.1 and Fig-5.1 also contain data on elemental abundances in the < 4 μm fraction of the bank sediments. The chemical composition of this fraction hold signatures of more intense weathering as it includes clays, which are some of the end products of silicate weathering. Na in the < 4 μm average 0.29±0.08 wt %, depleted by a factor ~ 4 compared to bank sediments from the same locations, whereas Fe and Al are enriched (8.1 ± 1.8 and 11.9 ± 0.7 wt% respectively) to a similar extent (Table-5.2). K also shows enrichment, however, to a lesser degree than that of Fe and Al. The enrichment in K may be due to its incorporation/adsorption in clays. The concentrations of Na and K in this fraction do not show any discernable trend with Al whereas Fe seems to exhibit a positive correlation (Fig-5.1). These results can be understood in terms of differences in the intensities of chemical weathering which mobilizes Na and K to different extent and concomitantly enriches Fe. The abundances of weathering resistant elements (Fe) and labile elements (Na, K and Ca) in the suspended load lie between the bank sediments and < 4 μm fraction. Such a trend is consistent with that expected as the suspended load contains components of both the bank sediments and their fine fractions (<4μm). These trends are born out in (element/Al) ratio plots of different sediment fractions/types analysed (Fig-5.1).

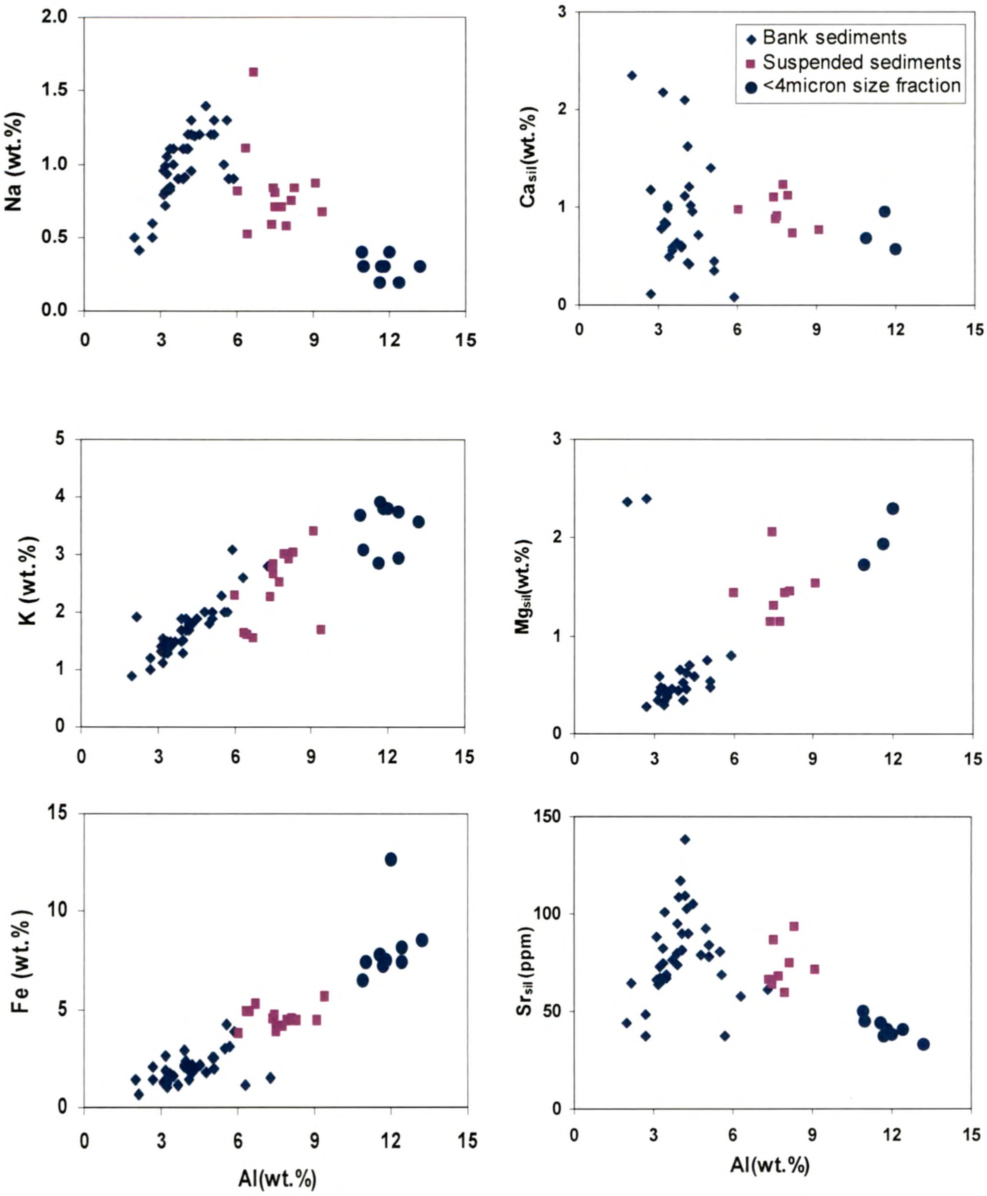

Fig-5.1: Scatter plots of Na, K , Fe, Ca$_{sil}$, and Mg$_{sil}$ wt (%) and Sr$_{sil}$ (ppm) abundances vs Al (wt %) in bank sediments, suspended load and <4µm of bank sediments. The subscript sil represents silicate component of the sediments.

Table-5.2: Average (±σ) composition of Himalayan Crystallines and the Ganga Sediments

Samples	**Al (%)**	**Fe (%)**	**Ca (%)**	**Mg (%)**	**K (%)**	**Na (%)**	**P (%)**
Rocks							
Higher Himalayan Crystallines (HHC) n = 99	6.9 ± 1.4	3.0 ±0.9	0.8 ±0.4	1.1 ± 0.6	2.5 ±0.5	1.7 ±0.4	0.02 ±0.04
HHC (Compiled) n = 56	7.3 ± 1.4	2.5 ±2.1	0.9 ±0.6	0.5 ± 0.6	3.6 ±1.0	2.4 ±0.9	-
LHC (Compiled) n = 108	7.2 ± 0.9	2.8 ±1.4	1.1 ±0.7	0.9 ± 0.7	4.0 ±1.1	2.1 ±0.9	-
Sediments							
Ganga Bank Sediments n = 37	4.2 ±1.0	2.0 ±0.8	2.1 ±1.4	0.7 ± 0.3	1.7 ±0.4	1.1 ± 0.3	0.05 ±0.01
Ganga Suspended Sediments n = 14	7.6±1.0	4.5±0.5	3.1±1.7	1.8±0.3	2.4±0.6	0.8±0.3	-
Ganga Bank Sediments (< 4μm) n=9	11.9 ±0.7	8.1 ±1.8	2.4 ±0.9	2.3 ±0.4	3.5 ±0.4	0.3 ±0.1	-

Source: Higher Himalayan Crystalline (HHC) n =99: France Lanord and Derry (1997) + Compiled from reference given in Krishnaswami et al., 1999. Sediment composition was measured in bulk (Total) samples; this work.

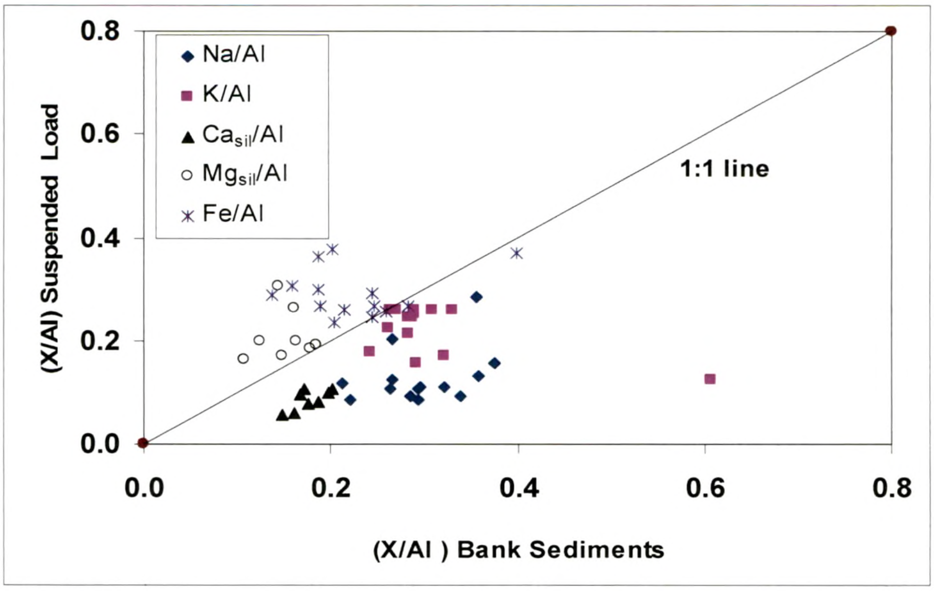

Fig-5.2: Element/Al ratios in bank and suspended sediments. Subscript sil represents carbonate corrected abundance. Na, K and Ca$_{sil}$ show a clear depletion in suspended sediments relative to bank sediments. In contrast, ratios of Fe and Mg$_{sil}$ with Al seem to indicate enrichment in suspended load.

Analogous to bank sediments, the data for suspended load also show a positive trend between K and Fe with Al indicating that for these elements, the effect of dilution over compensates the effect of chemical weathering. The elemental abundances in sediments and its components suggest that mobile elements such as Na are released to rivers from rocks during weathering, causing its depletion in the residual phase, the extent of depletion being dependent on the intensity of weathering. Further, the loss of major elements, Ca, Na, Si from rocks to rivers causes a concomitant increase in the concentration of immobile elements such as Fe and Al in the weathered residue (Tables-5.1& 2). Plots of silicate derived Ca$_{sil}$, Mg$_{sil}$ and Sr$_{sil}$ vs Al (Fig-5.1) shows that Mg exhibits a positive trend (except two samples from Birahi Ganga) and is less mobile as compared to Ca and Sr. This observation is consistent with the occurrence of Mg in some of the weathering resistant minerals such as amphibole, present in the Himalayan rocks. The higher mobility of Na and Ca from the bank sediments is also seen from their measured ratios with Al (Figs-5.2 & 5.3) indicating that there is significant loss of Na, Ca$_{sil}$ and K as bank sediments are converted to suspended sediments and <4μm size fraction.

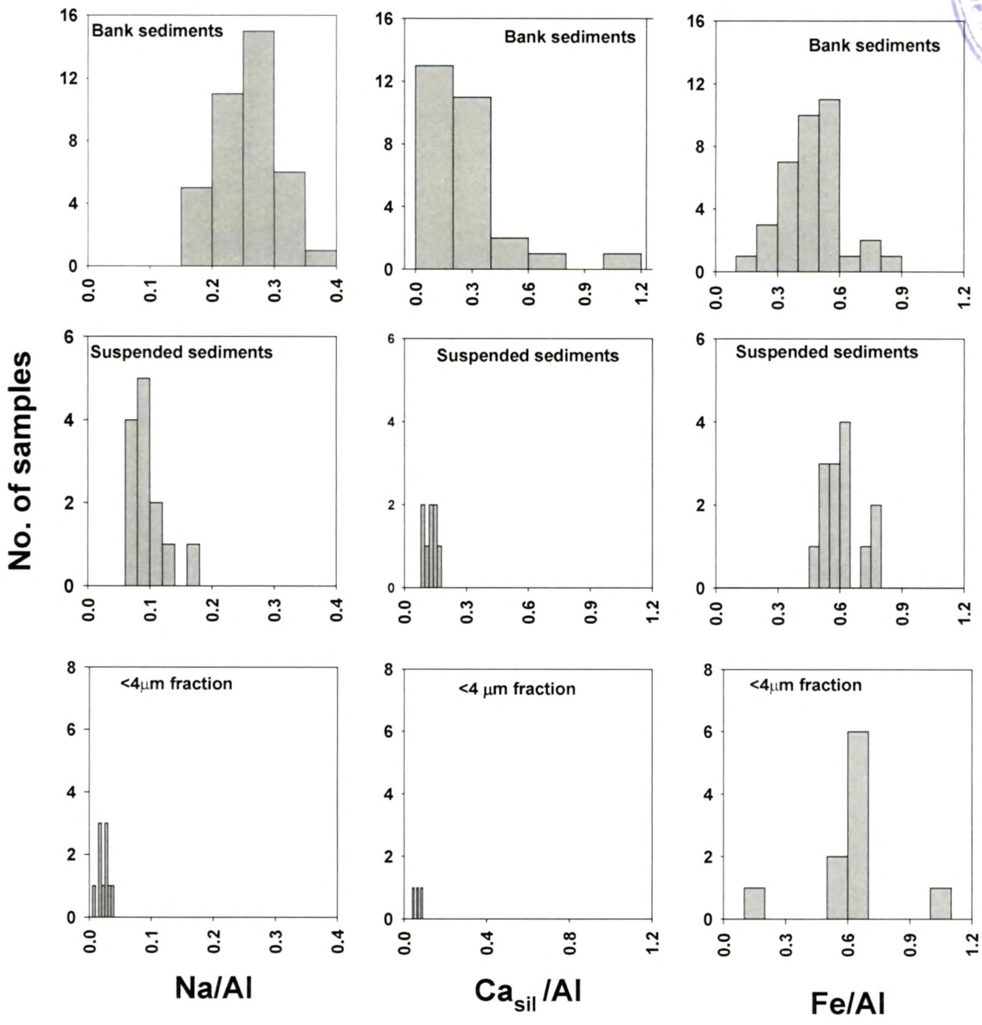

Fig-5.3: Frequency distribution of (element/Al) ratios in the Ganga sediments. Ca_{sil} is silicate derived Ca. A systematic decrease in Na/Al and Ca/Al from bank sediments to suspended sediments to <4μm bank sediments is clearly evident. The Fe/Al ratio does not seem to show any significant trend.

Based on average Na/Al and Ca_{sil}/Al ratios in bank and suspended sediments, it can be estimated that roughly about two thirds of Na and about a third of Ca are lost to rivers during chemical weathering.

5.2.2 Carbonates in the Ganga sediments.

The source of carbonates to the Ganga sediments can be from the Himalaya brought along with silicates during physical erosion or from those forming locally. Mineralogy of the Ganga sediments shows the presence of lithic carbonate fragments of in them (Garzanti et al., 2004). The local source of carbonate is relatively more pronounced in the Ganga plain. The alluvial sediments of the Ganga contain impure calcareous matter in the form of nodules/concretions in clays or as independent layers, locally known as "kankar" (Agarwal et al., 1992; Singh et al., 2004). The kankar carbonates are formed from river water/groundwater during their drying cycles and are widely dispersed in sediments of the plain (Agarwal et al., 1992; Srivastava, 2001; Sinha et al., 2006). The carbonates are predominantly calcium carbonate, though magnesium carbonate is also reported in some of them (Agarwal et al., 1992; Singh et al., 2004). The abundance of calcareous matter in the plain varies significantly, with values as high as 30% (Wadia, 1981; Gupta and Subramanian, 1994).

Data on the inorganic carbon (IC) content of the bank sediments and suspended loads (Table-5.1) is a measure of carbonates in them. IC displays large variation from as low as 0.003% to as high as 7.2 wt% (Table-5.1). This will translate to 0.03% to 60% carbonate if all of the IC is due to $CaCO_3$ and from 0.02% to 56% if all of IC is dolomite. Both dolomite and calcite exposures are abundant in the Lesser Himalaya (Singh et al., 1998; Bickle et al., 2001, 2003, 2005; Rai et al., 2008). Carbonates from Trans-Himalaya are generally more calcitic and in some of the rivers such as the Gandak its contribution can be significant (Galy, 1999). The sediment sample of the Bhagirathi, near it source, has very low carbonate whereas the Birahi Ganga draining though the Deoban dolomite formation of the inner Lesser Himalaya has the highest carbonate content among the samples analysed (Table-5.3). Attempts to apportion the carbonate into Ca and Mg carbonates were made by analysing mild acid leaches of sediments for their Ca and Mg contents. The results (Table-5.3) show that sediments of the Ganga headwaters and its Himalayan tributaries (Ghaghra, Gandak and Kosi) all have both Ca and Mg in them. The concentration of IC calculated based on measured Ca and Mg in the acid leaches show excellent agreement with those measured directly in the sediment samples by coulometry (Table-5.3 & Fig-5.4). This suggests that acid leaching procedure does not dissolve Ca and Mg from silicate phases to any measurable degree. The Ca/Mg molar ratio in the leach range between 1.0 to 9.3 with an average value of 3.1±1.8 for the Ganga system samples analysed.

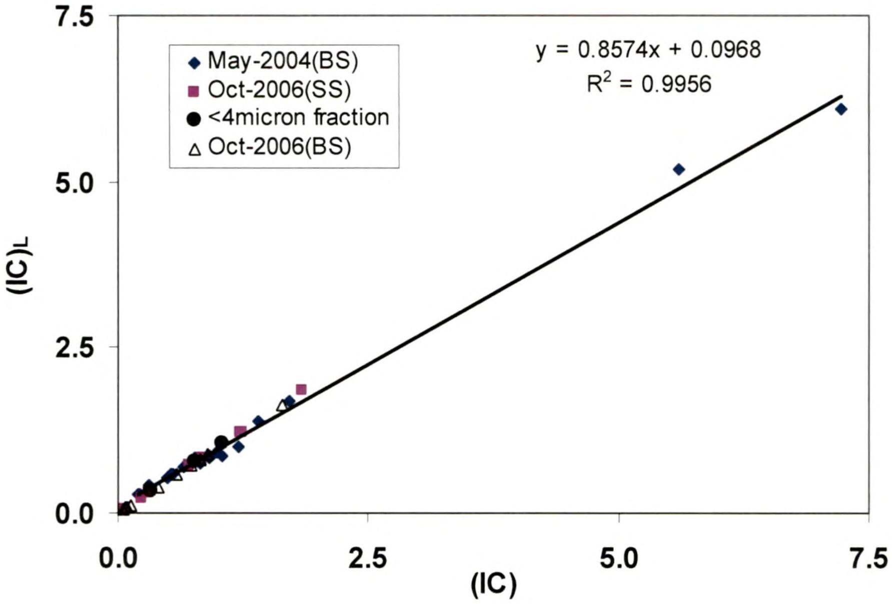

Fig-5.4: Scatter diagram of coulometer measured (IC) vs calculated $(IC)_L$ based on Ca and Mg in mild acid leach.

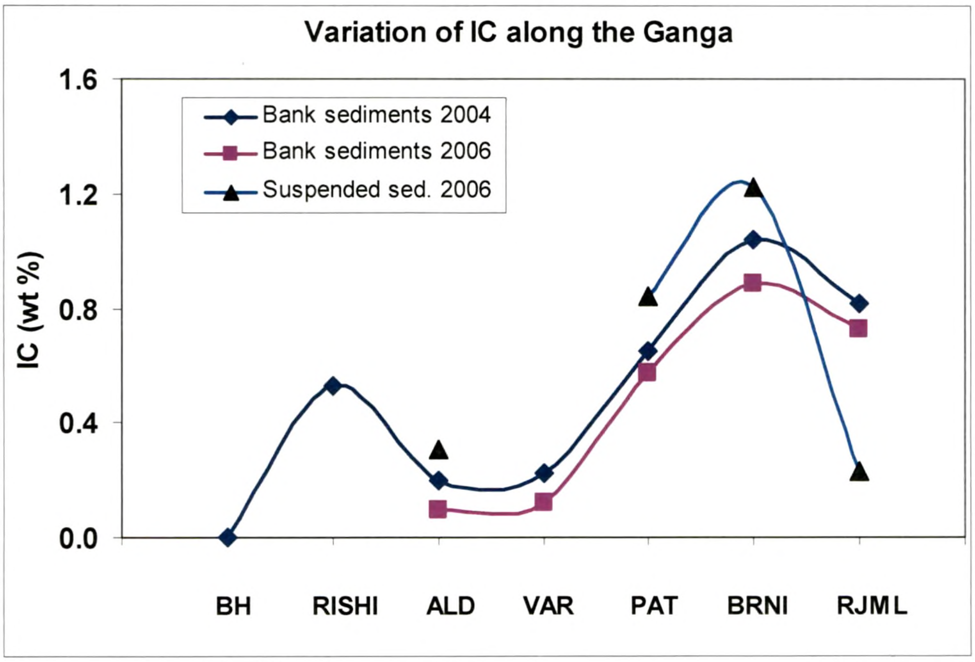

Fig-5.5: Variation of IC along the Ganga mainstream from its source to its outflow.

The lower Ca/Mg molar ratio ≈1 (Table-5.3) is in the sediments of Birahi, which also has the highest abundance of carbonate among the bank sediments analysed. The Yamuna and the Rapti sediments have much lower abundances of Mg carbonates, with Ca/Mg molar ratio of 8.6±0.9. The carbonates of the Yamuna are from Vindhyan sediments (Ray et al., 2003). The three samples from Ghaghra have Ca/Mg molar ratio in the range of 2.4 to 2.7 and two samples of the Gandak 5.7 to 6.0 (Table-5.3). These range of values among the replicates provide the overall variability in the ratios.

IC content of mainstream Ganga sediments (sampled during May 2004) steadily increases from 0.003% near its source (Gangotri), to ~0.5% at Rishikesh, near the foothills of the Himalaya (Fig-5.5), showing contribution from the Lesser Himalayan carbonates. In the Ganga mainstream, at Allahabad IC is ~0.2 wt% which steadily increases to a value of ~0.65 at Patna and to 1.04 wt% at Barauni, before attaining a value of ~0.82 (wt%) at the outflow near Farakka. The increase in carbonate abundance between Allahabad and Barauni is a result of contributions from the Ghaghra and the Gandak rivers.

Table-5.3: IC concentration in bank sediments: comparison of measured and calculated from Ca and Mg in acid leaches.

					(0.6N HCl) Leach		
Sample	**Location**	**River**	**IC$^+$** (wt%)	**$(IC)_L$*** (wt%)	**Ca_L** (wt%)	**Mg_L** (wt%)	**Ca/Mg** (Molar)
RS03-1	Rishikesh	Ganga	0.53	0.59	1.25	0.43	1.76
BR352	Allahabad	Ganga	0.2	0.26	0.49	0.24	1.26
BR382	Varanasi	Ganga	0.22	0.28	0.72	0.13	3.27
BR306	Patna	Ganga	0.65	0.69	1.69	0.37	2.79
BR315	Barauni	Ganga	1.04	0.84	2.19	0.38	3.49
BR324	Rajmahal	Ganga	0.82	0.74	1.9	0.35	3.29
RS03-28	Birhai, B.confl	Alaknanda	0.76	0.83	1.85	0.57	1.97
RS03-27	Birhai	Birahi Ganga	5.61	5.19	8.93	5.11	1.06
RS03-29	Birahi	Birahi Ganga	7.23	6.09	10.05	6.24	0.98
RS03-31	Pindar Valley	Pindar	1.21	0.98	2.2	0.65	2.06
BR348	Allahabad	Yamuna	0.5	0.53	1.6	0.1	9.32
BR365	Gorakhpur	Rapti	0.55	0.57	1.7	0.13	7.98
BR378	Before Confl.	Gomti	0.34	0.39	1.06	0.15	4.19
BR355	Ayodhya	Ghaghra	0.91	0.86	2.04	0.52	2.4
BR371	Doharighat	Ghaghra	0.99	0.92	2.16	0.55	2.39
BR343	Revelganj	Ghaghra	0.91	0.83	2.01	0.46	2.67
BR336	Barauli	Gandak	1.41	1.37	3.88	0.41	5.71
BR310	Hajipur	Gandak	1.72	1.67	4.79	0.48	6.04
BR331	Dumariaghat	Kosi	0.31	0.41	1.02	0.2	3.07

$^+$IC-measured by coulometry (wt%) in sediments ; *$(IC)_L$: calculated from Ca_L and Mg_L

The detrital carbonates are finally transported to the Bay of Bengal. The role of these carbonates in contributing to the inorganic carbon content of the Bay of Bengal Fan sediments are discussed briefly in section 5.5.

5.3 Weathering Intensity of the Ganga Sediments

Rocks from the Himalaya are being eroded by both physical and chemical weathering. Chemical Index of Alteration (CIA; Nesbitt and Young, 1982) provides a measure of chemical weathering intensity of sediments. It is given by:

$$CIA = 100\left(\frac{(\mathrm{Al_2O_3})}{(\mathrm{Al_2O_3} + \mathrm{Na_2O} + \mathrm{K_2O} + \mathrm{CaO}^*)}\right) \qquad \ldots\ldots\ldots\ldots\ldots\ldots (5.1)$$

where concentrations of all elements are in mole % and CaO* is CaO content of silicates. To determine CIA of the Ganga sediments, their CaO* content was calculated by subtracting from the measured CaO, the CaO of carbonate origin. The carbonate Ca in samples was determined by mild acid leach (0.6N HCl) of sediments as discussed in previous section and given in Table-5.3. Using these values the CIA for the bank sediments is calculated to vary from 31 to 64 with an average of 52±6 (Table-5.4).

Among the samples analysed, the lowest CIA (31) was observed for the Birahi Ganga sediment and the highest for the Kosi (64). The CIA of the bank sediments generally overlaps with those of their source rocks in the Himalaya (Table-5.4). This similarity in CIA values (CIA~ 59) of source rocks (crystallines from the Himalaya) and the bank sediments (Table-5.4) suggests that on average these sediments have not undergone measurable chemical weathering. As result the chemical composition of these bank sediments can serve as representative of the source rocks from which they are derived.

In contrast, the CIA values of suspended sediments and <4μm fraction of bank sediments are higher than both source rocks and bank sediments. This suggests that these sediments have been subjected to more intense chemical weathering resulting in the loss of Na and Ca. This is consistent with the inferences drawn from major element data (section-5.2.1).

Table-5.4: Comparison of CIA of different lithologies and sediments from the Ganga system

Region/ Basin	**(n)**	**Sample**	**CIA** Range	**CIA** Mean	**CIA*** Mean	**Data source**
HHC	99	Total		59	65	France-Lanord and Derry, 1997
Lesser Himalaya	75	Meta Sediments	24-73	53±8	58±9	Rawat 1984; Mishra, 1973; Kashyap 1972
Lesser Himalaya	108	Granites/ Gneisses	21-70	52±7	58±7	Rao (1983), Gupta1994, Nautiyal, 1990 ,
Higher Himalaya	56	Granites/ Gneisses	29-83	53±7	58±6	Chamyal 1996 ; Choudhuri 1991, Scaliet et al., 1990 ; Rao, 1983
Thar Deseart		(Aerosols)	57-67			Yadava and Rajamani, 2004
Yamuna (Headwaters)		Bank Sediments	51-69	60±9		Dalai et al., 2001
Chambal		Bank Sediments	59-82	74±1		Rengarajan, 2004
Indus		Suspended Sediments	60			Ahmad et al., 1998
Ganga Sediments	28	Bank Sediments	31-64	52±6	63±2	This Study
Ganga Sediments	8	Suspended Sediments	61-68	65±2	73±2	This Study
Ganga Sediments	3	<4µm size fraction	73-76	75±2	81±3	This Study

All Ca in crystalline rocks taken as silicate Ca..

Colin et al. (1999) introduced the concept of *modified chemical index of alteration* CIA* as given by:

$$CIA^* = 100\left(\frac{(\mathrm{Al_2O_3})}{(\mathrm{Al_2O_3} + \mathrm{Na_2O} + \mathrm{K_2O})}\right) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ (5.2)$$

This concept was introduced to avoid the uncertainties associated with decoupling the CaO in sediments into its silicate and carbonate derived components. The CIA* value of the bank sediments range between 59 to 68, and average 63±2, overlapping within errors with that of the crystallines from the Himalaya, 58±6 (Table-5.4) and that reported for HHC (65, France Lanord and Derry, 1997). The close similarity in CIA* values between the crystallines of the Himalaya and the Ganga bank sediments confirm the earlier interpretation based on CIA that the bank sediments have not undergone measurable chemical weathering. In comparison to the bank sediments, the suspended sediments of these rivers have higher CIA* values averaging 74±3, again consistent with the interpretation based on CIA that the suspended loads have been subjected to significant chemical weathering. CIA* values of < 4 μm fraction ranges from 78-85, such high values indicate very intense weathering of source rocks, an inference consistent with major element data discussed earlier.

5.4 Composition of Sediments and Silicate weathering flux

Conventionally silicate erosion rates (SER) of river basins are calculated from dissolved major ion data of rivers using the relation:

$$(SER) = (Q/A)[(Na_{sil}+Mg_{sil}+ Ca_{sil} + K_{sil}) + SiO_2] \quad ....(5.3)$$

Q is the water discharge and A is the drainage area, therefore Q/A is runoff. Na_{sil}, K_{sil}, Mg_{sil} and Ca_{sil} are the elemental concentration in rivers derived from silicate weathering. Generally, Na_{sil} is assumed to be equal to chloride corrected Na concentration in river $Na_{sil} = (Na_r\text{-}Cl_r)$. The silicate erosion fluxes of the elements are estimated using Na_{sil} as an index and assigned values for (Ca/Na) and (Mg/Na) in the silicates undergoing weathering (Singh et al., 1998; Galy and France-Lanord, 1999; Krishnaswami et al 1999). This approach provides contemporary silicate weathering flux, the reliability of which depends on the source apportionment of Na to rivers and (element/Na) ratios in various end members. Another potential approach to obtain silicate erosion fluxes is based on the chemistry of suspended matter and source rocks. This approach was used by McCauley and DePaolo, (1997) to derive alkalinity fluxes to the Bay of Bengal based on sediment composition. The accuracy of estimated erosion rates by this approach depends on the knowledge of representative composition of source rocks and suspended matter and the annual flux of suspended matter. In this work, the composition of bank sediments are taken as representative of the source rocks. These sediments as discussed earlier are not weathered measurably, based on CIA values and their Sr and Nd isotopic composition.

The erosion rate derived by this approach average represents over the residence time of particulate phase transported by the rivers. In case of the Ganga, the residence time of particulate phase in the Himalayan sub-basins is expected to be quite small due to high relief (chapter-3, section 3.2.7) and intense precipitation. In contrast the residence time of particulate phase in the Ganga plain could be higher. Indeed, the work of Granet et al. (2007) based on U-Th isotope systematics on the Ganga bank sediments show that their residence time (transport of sediment in rivers including temporary stay of particles in alluvial plain and re-mobilisation to the river) in the basin can be of the order of a few thousand years.

In this study, the erosion fluxes have been calculated after normalizing the chemical abundances with respect to Al to correct for effects of mineralogical changes/dilution. The corrected elemental ratios, representing silicate component, are given in Table-5.5a. In addition, attempts to derive an "average" $(Ca/Al)_{sil}$ and $(Mg/Al)_{sil}$ in the bank (n=32) and suspended (n=12) sediments were made by regression analysis of (X/Al) vs (IC/Al) data (X is Ca or Mg) . This approach assumes that Ca and Mg in sediments analysed are sourced only from silicates and carbonates. In such a case, the intercept of the Ca(Mg)/Al vs IC/Al lines would yield average Ca/Al, Mg/Al in silicate fraction of the sediments. This approach was more satisfactory for Ca, as the data show a strong correlation (Fig-5.6) whereas for Mg, the regression has considerable scatter. Therefore this approach was used only for deriving the average Ca/Al in the silicate fraction bank and suspended sediments. The intercepts of the (Ca/Al)-(IC/Al) plot for bank and suspended sediments give values of 0.189±0.036 and 0.100±0.021 respectively for (Ca/Al) ratio in silicates.

The (Mg/Al)-(IC/Al) plots of both bank and suspended sediments have large scatter. The regression seems to indicate an enrichment of Mg in the suspended phase relative to bank sediments as observed earlier (Fig-5.2). The (Na,K)/Al, ratio in suspended load is based on the Rajmahal sample (at the out flow of the Ganga). The data in Table-5.5a show, as expected that the Ca_{sil}/Al, Na/Al and K/Al ratios in the suspended load is less than that in bank sediments resulting from loss of Ca, Na and K to rivers during weathering. Among these ratios, the differences in the K/Al ratios between bank sediments and suspended load is the lowest, consistent with its relatively lower mobility.

Table-5.5a: (Element/Al) ratios in silicate component of sediments from the Ganga river

Ratio (wt/wt)	Bank sediments (BS)	Suspended Sed. (SS)	(BS-SS)
Ca/Al	0.189±0.036	0.100±0.021	0.089 ±0.042
Na/Al	0.253±0.044	0.090±0.009	0.163 ±0.045
K/Al	0.411±0.041	0.355±0.036	0.056 ±0.055

The silicate erosion fluxes for the Ganga basin has been calculated based on data in Table-5.5a and using the relation:

$$F_i = \left(R_b^i - R_s^i\right)C_{Al}.F_{ss} \qquad \text{............(5.4)}$$

where F_i, is annual erosion flux of element i derived from silicates, R^i is the ratio of element i with respect to Al, C_{Al} is Al concentration in suspended load at out flow (Rajmahal, 8.2 wt%) and F_{ss} is the annual suspended sediment flux transported by the Ganga. The subscripts b and s stands for bank and suspended sediment respectively. Uncertainties on the estimated loss of cations (Table-5.5b) were made by appropriately propagating the errors associated with element/Al ratios in bank and suspended sediments. Using a value of ~ 500 million tons yr^{-1} for F_{ss} (Galy and France-Lanord, 2001) the fluxes of Na, K and Ca due to silicate erosion are estimated to be $(2.9\pm0.5)\times10^{11}$, $(5.9\pm5.6)\times10^{10}$ and $(9.1\pm4.3)\times10^{10}$ moles yr^{-1} respectively resulting a CO_2 consumption of $(5.3\pm1.1)\times10^{5}$ moles km^{-2} yr^{-1} (Table-5.5b). (The value 500 million tons yr^{-1} for suspended load flux when combined with an equivalent a value for bed load flux yield a value of ~ 1000 million tons yr^{-1} for sediment flux from the Ganga to the Bay of Bengal, as used in chapter-3). The annual silicate erosion fluxes of Ca, Na and K derived from this study based on sediment composition are compared with those based on water data (calculated from Sarin et al 1989 and this study; Table-5.5b). The results show that erosion fluxes of Ca derived from sediment data are in agreement with the water data, where as for Na and K the sediments based fluxes are a factor of ~2 higher than that derived from water data.

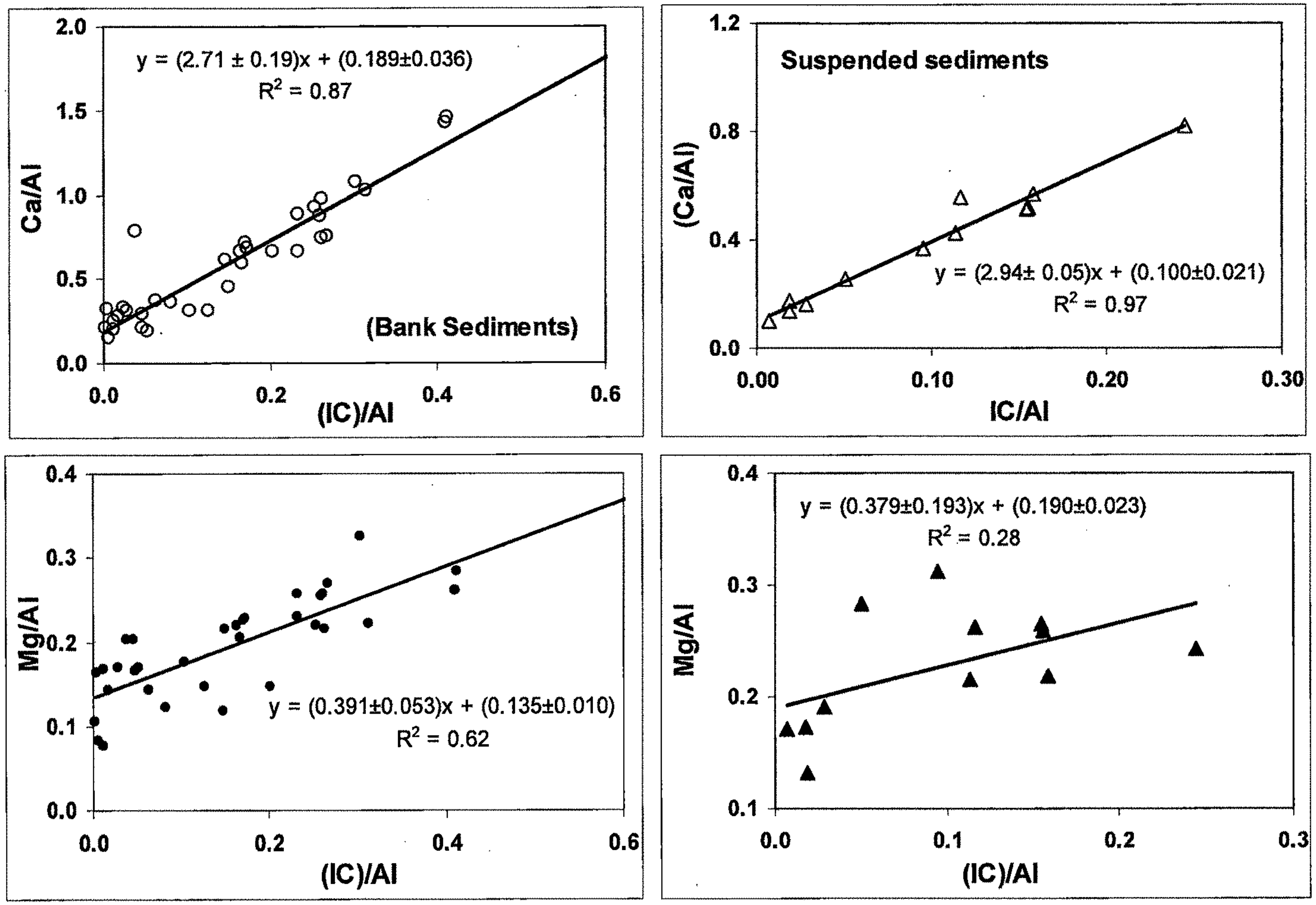

Fig-5.6: Scatter plots of Ca/Al and Mg/Al with (IC/Al) in the Ganga bank and suspended sediments (all in wt%). The intercept represents the elemental ratios in the silicate component. (Ca/Al) data show a much better fit with (IC/Al).

The weathering flux of K, however, overlaps within errors with the water derived values. The total alkalinity flux from silicates of the Ganga sediments is ~ (5.3±1.1)x10^{11} eq yr^{-1}. McCauley and DePaolo (1997) derived alkalinity fluxes from the Ganga-Brahmaputra rivers to the Bay of Bengal based on cation deficit in the Bay of Bengal sediments relative to the source rocks in the Himalaya. They reported an average loss of ~0.25 eq. alkalinity per mole of Al in the clay and silt fraction of the fan sediments corresponding to an alkalinity flux of 3.25x10^{11} eq yr^{-1} over the past ~40 Ma.

Table-5.5b: Silicate weathering flux and associated CO_2 consumption in the Ganga Basin

Silicate Flux	From sediments	From dissolved major ions in river water	
Element	**This study** moles yr^{-1}	**This study** moles yr^{-1}	**Sarin et al -1989** moles yr^{-1}
Ca	(9.1±4.3)E+10	(6.4±2.7)E+10	(7.9±3.4)E+10
Na	(2.9±0.5)E+11	9.1E+10	1.1E+11
K	(5.9±5.6)E+10	2.4E+10	2.2E+10
CO_2 consumption (moles km^{-2} yr^{-1})	**(5.3±1.1)E+05**	**(2.4±0.5)E+05**	**(2.9±0.7)E+05**

The observation that the sediment based Na flux is a factor of ~2 higher than the value derived from water data is a concern. This is because dissolved Na flux may have contribution from alkaline/ saline soils which would make the estimates of silicate erosion flux based on chloride corrected Na in water on the higher side. If such a correction is indeed warranted then the difference in the Na flux derived from sediment and data water data would become even larger. The impact of such alkaline/saline salts is likely to be more on the data of Sarin et al. (1989) as it is based on samples from Patna, a location closer to the confluence of the Ganga and the Yamuna rivers, where the major ion chemistry are known to influenced by alkaline/saline salts (chapter-4). Potential causes for the discrepancy between water and sediment based fluxes include (i) sample heterogeneity. The current estimate (Table-5.5b) rely on a single sample of suspended sediments collected at Rajmahal (ii) uncertainties in end member elemental ratios used in calculations in the water data based estimates (iii) temporal variations in silicate erosion. (iv) errors associated with suspended sediment flux estimates. The sediment based fluxes represent values averaged over time periods corresponding to their residence time in the basin whereas the water based fluxes are contemporary. More studies are needed to reduce the uncertainties in both the estimates through better sampling and analysis and by constraining the end member values. If the results are encouraging then the use of sediments to obtain paleosilicate erosion data can be explored.

5.5 Particulate Organic and Inorganic Carbon (POC and PIC) fluxes from the Ganga Basin.

Organic carbon (particulate and dissolved, POC and DOC) enters rivers from the erosion of soils, sedimentary rocks and plant debris in the catchment. Sediments supplied by the Ganga-Brahmaputra Rivers (G-B) to the Bay of Bengal contain significant amount of organic and inorganic carbon. The transfer of carbon from the land to the oceans via fluvial systems is a key link in the global carbon cycle (Ittekot and Haake 1990; Hedges et al 1992, Galy et al., 2007). Burial of organic carbon in the coastal ocean is one of the mechanisms for sequestration of atmospheric CO_2 (France Lanord and Derry, 1997; Keil et al., 1997; Richey et al., 2002). Export and burial of POC from the G-B system and some of their tributaries have been studied by earlier workers yielding a range of values for their fluxes (Ittekkot et al., 1985, Subramanian et al., 1985, France-Lanord and Derry, 1994, 1997; Aucour et al., 2006; Galy et al., 2007). Aucour et al. (2006) derived a total organic carbon flux of ~6 million tons yr^{-1} to the Bay of Bengal via suspended load of the G-B system. However this may be an underestimate for the POC flux as this does not consider the sequestration of organic carbon in flood plains or their transport through bed load. Subramanian et al. (1985) have estimated a higher POC flux of 36 million tons yr^{-1} for the G-B system, based on an OC content of 1–2% for suspended load at the river mouth.

Further, these studies have indicated that transport of particulate organic carbon is medium dependent (i.e. bed load, suspended load).

As a part of this thesis, investigation on the transport and fluxes of particulate organic carbon through the Ganga to the Bay of Bengal has been carried out. Towards this, particulate organic carbon measurements were made on bank sediments, suspended sediments and <4μm fraction of the bank sediments along the Ganga mainstream and its tributaries.

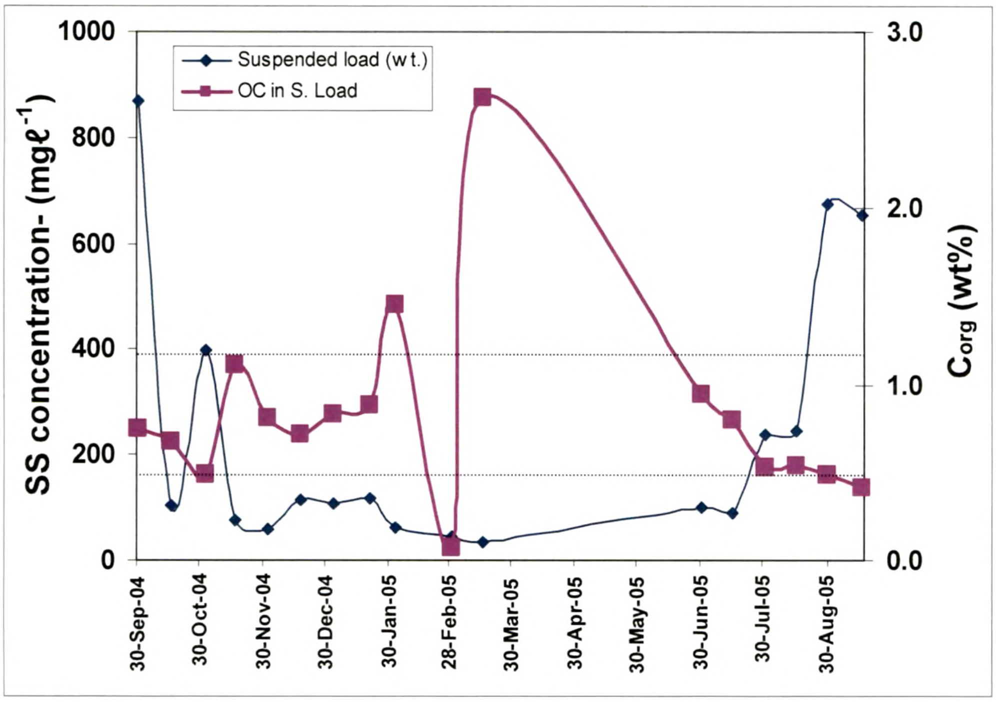

Fig-5.7: Temporal variation of suspended load (mg ℓ^{-1}) and organic carbon content (wt%) in the Ganga mainstream at Allahabad. The data though show a large range in organic carbon content of the suspended load, most of the samples have C_{org} in the range of 0.5 wt% to 1.2 wt% (dotted lines).

Further, organic carbon content of suspended sediments has been determined on biweekly time series measurement over 10 months at Allahabad in the Ganga mainstream (Fig-5.7). The suspended load concentrations vary from 34 to 870 mg ℓ^{-1} and C_{org} from 0.1 to 2.6 wt%. The C_{org} content of the samples, except a few, are within a range of ~0.5 to 1.2 wt%. There seems to be an indication that organic carbon content in the suspended sediments is generally lower during monsoon, likely to be due to intense physical erosion which dilutes organic carbon with silicate particulates. The C_{org} content of bank sediments ranges from 0.02 to 0.26 wt% (excluding the Birahi Ganga and the Bhilangana which have 1.9 and 1.6 wt% respectively) with an average 0.12±0.07 wt%. The C_{org} content of bank sediment samples in May 2004 and Oct 2006 though are in the same range, the values from the same location vary by factors of ~0.4 to 4 (Fig-5.8) bringing out the high temporal variability in C_{org}. The range and average POC contents of various sediments analysed are given in table 5.6. The C_{org} content of bank sediments is significantly lower than the C_{org} abundances in suspended load and <4µm fraction of the bank sediments (Table-5.6; Fig-5.8).

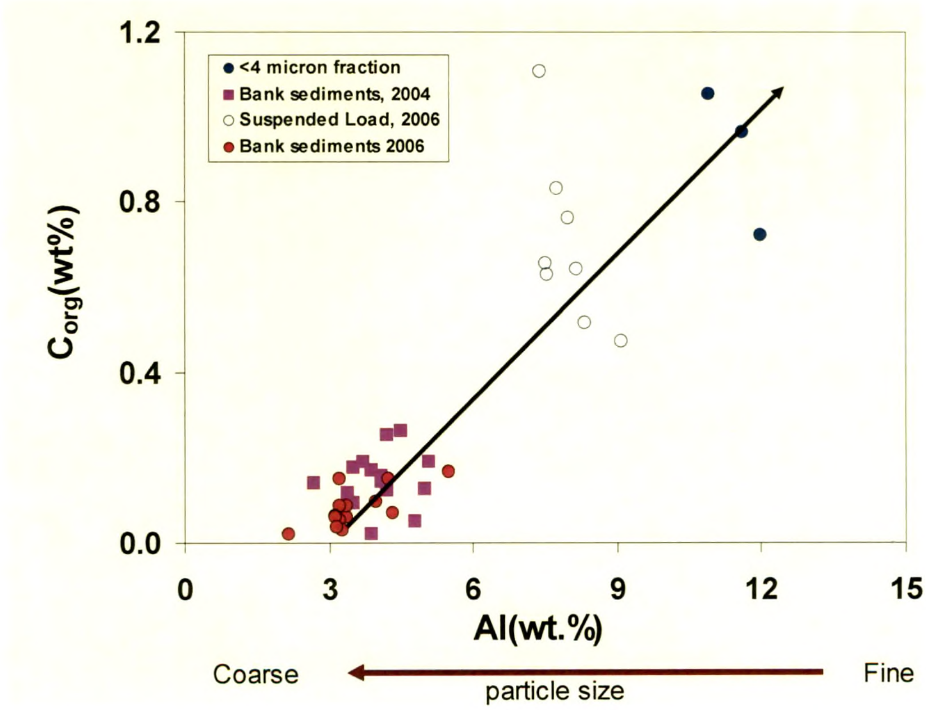

Fig-5.8: Variation of C_{org} with Al in different components of the Ganga river sediments. The plot shows that organic carbon content increases with Al, (i.e. decreasing particle size). A few samples which have C_{org} > 1.2% are not plotted (Table-5.1)

The scatter plot of POC vs Al abundance show that the three fractions, bank sediment, suspended sediments and the < 4μm fall in three distinct groups with lowest value for bank sediments and highest for <4μm fraction (Fig-5.8). As expected, the suspended sediments fall between the bank sediments and its < 4μm fraction as it is a mixture of these two end members. Fig-5.8 shows that C_{org} increases with Al content. Al is relatively enriched in finer particles because of its weathering resistant property. The POC-Al trend can, therefore, be interpreted in terms of an inverse relation between organic carbon abundance and size of particles. Adsorption of organic matter on clays and fine particles which have larger surface area contribute to the trend in Fig-5.8 (Keil et al 1997, Aufdenkampe et al 2001). The POC contents of bank and suspended sediments at Rajmahal (0.14 and 0.64 wt %, Table-5.1) along with the reported annual sediment flux of the Ganga (500 million tons for bed load + 500 million tons suspended load) yield a value of ~4 million tons yr^{-1} for POC flux from the Ganga to the Bay of Bengal. If 50% uncertainty is assigned to this value due to potential spatial and temporal POC flux and that observed for suspended sediments (Table-5.6), variability in the flux would be ~4±2 million tons yr^{-1}.

Table-5.6: C_{org} abundance in Ganga sediments (wt%):

Sample	n	range	average
Bank sediments	39	0.001-0.26	0.12±0.07
Suspended sediments	12	0.47-2.20	1.02±0.57
<4μm fraction	3	0.72-1.06	0.91±0.17

However, most of the particulate organic carbon (~90%) is transported via suspended load. The POC flux from the Ganga is within the range of ~ 1.5 to 3 wt% of the global particulate organic carbon (POC) supply (138-288 million tons yr^{-1}) via rivers to the world oceans (Ittekkot and Laane 1991, Spitzy and Ittekkot, 1991). The POC flux from the Ganga is of the similar magnitude as that of its CO_2 consumption by silicate weathering. Estimates for the long term (last ~13 Ma) burial flux of organic carbon for the G-B system is ~13 million tons yr^{-1} (France

Lanord and Derry, 1997). However, more recent study of Galy et al. (2007) reports a burial flux of ~7 million tons yr^{-1}. Burial efficiency of particulate organic matter transported by rivers to the coastal ocean varies between 25-90% (Keil et al 1997, France Lanord and Derry 1997, Galy et al., 2007). For a burial efficiency of 50%, the burial flux of POC of the Ganga would be ~2 million tons yr^{-1}.

Another component of particulate carbon in river sediments is carbonates which are abundant in the drainage basin of the Ganga, particularly in the Lesser Himalaya. The abundance of inorganic carbon in bank sediments along the course of Ganga in the Himalaya, as mentioned earlier in this chapter (section-5.2.2) show an overall increase, from 0.003 wt% at its source (Gangotri) to ~ 0.53 wt% at the foothills of the Himalaya (Rishikesh). The Yamuna, the Ghaghra and the Gandak bank sediments also have significant inorganic carbon (0.4 -1.8 wt %) in them whereas the Kosi bank sediments have only ~0.04% carbonates. The IC content of the bank sediments of the Ganga mainstream in the plain varies from 0.1% to 1.2% with a value of 0.8 wt% at Rajmahal. This is in contrast to the POC which is more abundant in fine particle size. The difference is because carbonates are supplied to sediments mainly via mechanical erosion in the Himalaya and the plain along with silicates.

Compared to the Ganga System, the abundance of IC in the Brahmaputra bank sediments is less (<0.07%) (Galy 1999; Singh and France-Lanord 2002) as the Brahmaputra waters, analogous to the Kosi waters, are under-saturated in $CaCO_3$. Further, the exposure of the Lesser Himalaya carbonates in the Brahmaputra catchment is also relatively less. The Bay of Bengal sediments receive inorganic carbon from two sources (i) detrital carbonates from the drainage basin transported by the Ganga system and (ii) the sinking of carbonate shells produced in overlying water column through primary productivity. This study places constraints the role of detrital input of carbonates to the Bay of Bengal sediments.

The IC concentration of 0.8 wt% at Rajmahal corresponds to ~5 wt% calcium carbonate based on (Ca/Mg) molar ratio of 3.3 (Table-5.3). This gets diluted to ~1-2 wt% after confluence with the Brahmaputra. Based on a calcium carbonate concentration of 1-2 wt% in G-B particulates and total sediment flux of 2000 million tons yr^{-1} (Ganga and Brahmaputra together, Hay, 1998), the carbonate flux to the Bay of Bengal can be estimated to be 20-40 million tons yr^{-1}. This flux corresponds to 0.16 -0.32% of the sinking carbonate flux (IC~1.8 g $m^2 d^{-1}$; Ittekot et al., 1991) in the Bay of Bengal with area ~$2.2x10^6$ km^2 (Fairbridge et al., 1966).

5.6 Summary:

Chemical composition of sediments from the Ganga and its tributaries were used to assess the weathering intensities of different components. Based on CIA and CIA* of these sediments and the source rocks in the Himalaya, It is demonstrated that the bank sediments of the Ganga and its tributaries have suffered only mechanical erosion without significant chemical weathering. Therefore, the chemistry of bank sediment can serve as representative of the source rocks. The suspended sediments and the <4m fraction of bank sediments show that they have undergone significant chemical weathering resulting in the loss of Na, K and Ca from them to rivers. Differences in the elemental abundance between bank sediments and suspended load have been used to estimate the relative loss of silicate derived elements during chemical erosion. The results show that erosion fluxes estimated from sediment data overlaps with the river water data for K and Ca within errors and are a factor of ~2 higher for Na. Additional data, based on better spatial and temporal coverage of suspended sediment samples is required to obtain more robust estimates of sediment based fluxes. Particulate organic (POC) and inorganic carbon (PIC) fluxes for the Ganga were also estimated. The results show that if most of POC transported by the Ganga is buried in Bay of Bengal sediments carbon sequestration by POC burial will be comparable to that of CO_2 consumption by silicate weathering in the Ganga basin. The flux of IC transported by the Ganga amounts to ~4 million tons yr^{-1}, this accounts for << 1% IC flux depositing in the Bay of Bengal.