Chapter 3

Sr and Nd isotopes in river sediments from the Ganga Basin: Sediment Provenance and Spatial Variability in Physical Erosion

3.1 Introduction

This chapter presents results on Sr and Nd isotopic composition and major element abundances in sediments from the Ganga mainstream and its tributaries. These results are interpreted to derive quantitative information on the provenance of sediments in the Ganga plain and spatial variability in physical erosion among its sub - basins. The Himalaya is drained by many rivers, the Ganga and the Brahmaputra being two of the major river systems. These two rivers together annually discharge ~ 100 million tons of dissolved solids (Sarin et al., 1989; Galy and France-Lanord, 1999; Galy and France-Lanord, 2001) and ~ 1000-2300 million tons of sediments (Hay, 1998, Islam et al., 1999; Galy and France-Lanord, 2001). It is evident from these solute and sediment fluxes that physical erosion accounts for ~90% of total erosion in their basins. The available data on sediment fluxes of the Ganga and the Brahmaputra (Hay, 1998; Galy and France-Lanord, 2001), though limited, seem to indicate that the Brahmaputra basin is eroding more rapidly (average ~3 mm yr^{-1}) than the Ganga basin (average ~2 mm yr^{-1}) due to the combined influence of climate and tectonics. Further, studies of spatial variations in physical erosion among the sub-basins of the Brahmaputra show that it is highly variable, with the Eastern Syntaxis region undergoing the maximum erosion of ~14 mm yr^{-1} (Singh and France-Lanord, 2002; Garzanti et al., 2004; Singh, 2006). In contrast to the Brahmaputra basin, information on the spatial variability of erosion rates in the Ganga basin is sparse, though such variations can be expected considering the differences in climate and relief among its sub-basins. Further, such data on basin-scale erosion rates would help constrain the effects of erosion on regional morphology, particularly pertaining to local uplift (Finlayson et al., 2002) and the relative significance of climate, tectonics and stream power in regulating erosion in the region (Singh and France-Lanord, 2002; Burbank et al., 2003; Molnar, 2003; Wobus et al., 2003; Craddock et al., 2007).

Sr and Nd isotope studies of sediments from the Bay of Bengal (France-Lanord et al., 1993) and the Brahmaputra basin (Singh and France-Lanord, 2002) suggest that the sediment budget in these basins is dominated by supply from the Higher Himalaya. Similarly, the limited available results (Galy, 1999; Galy and France-Lanord, 2001) from the Ganga basin in Bangladesh also seem to show the dominance of the Higher Himalayan source in its sediment budget, but the contributing role of various sub-basins is only poorly understood. A detailed and comprehensive study of the chemical and Sr and Nd isotopic composition of sediments from the Ganga system and its major tributaries (Fig-3.1& Fig-3.2) has been carried out to address some of these issues, particularly to (i) trace the sources of contemporary sediments to the rivers of the Ganga System and the Ganga mainstream in the plain in terms of major geological units, (ii) determine the fraction of sediments supplied from various sub-basins to the Ganga in the plain and (iii) estimate physical erosion rates over the western and the central Himalaya to assess their spatial variability, their controlling factors and their impact on regional geomorphology.

3.2 Results and Discussion

Sr and Nd concentrations and their isotope compositions have been measured in *silicate fraction* of the bulk and <4 µm sediments of the Ganga River, from Gangotri to Rajmahal, and its tributaries to determine provenance and the spatial variability in physical erosion among the Ganga sub-basins. The sediment samples, as mentioned earlier in chapter-2 (section 2.4.2) are from river banks within a few meter of water. The <4 µm fraction was separated from the sediments by gravitational settling in water. The abundance of <4 µm fraction in all sediments were low. Analysis of the <4 µm fraction was done to obtain data on fine fraction of sediments, which generally is an important component of riverine suspended matter. In samples from the upper reaches (i.e., upstream of Rishikesh, Fig-3.1) it was almost absent and hence in many of them only total sediment analyses could be made.

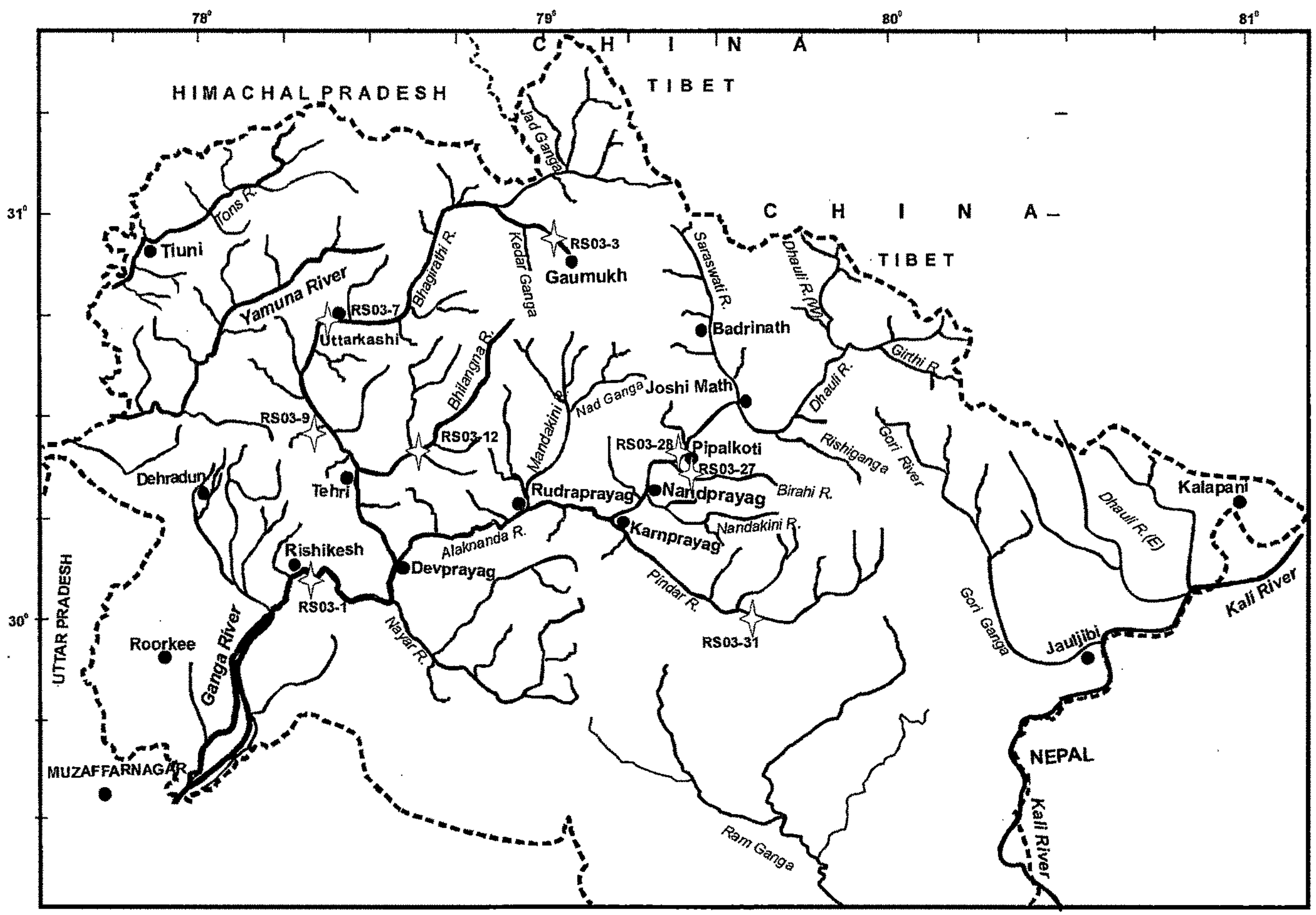

Fig- 3.1: Sampling locations of sediments from the Ganga basin in its Himalayan drainage.

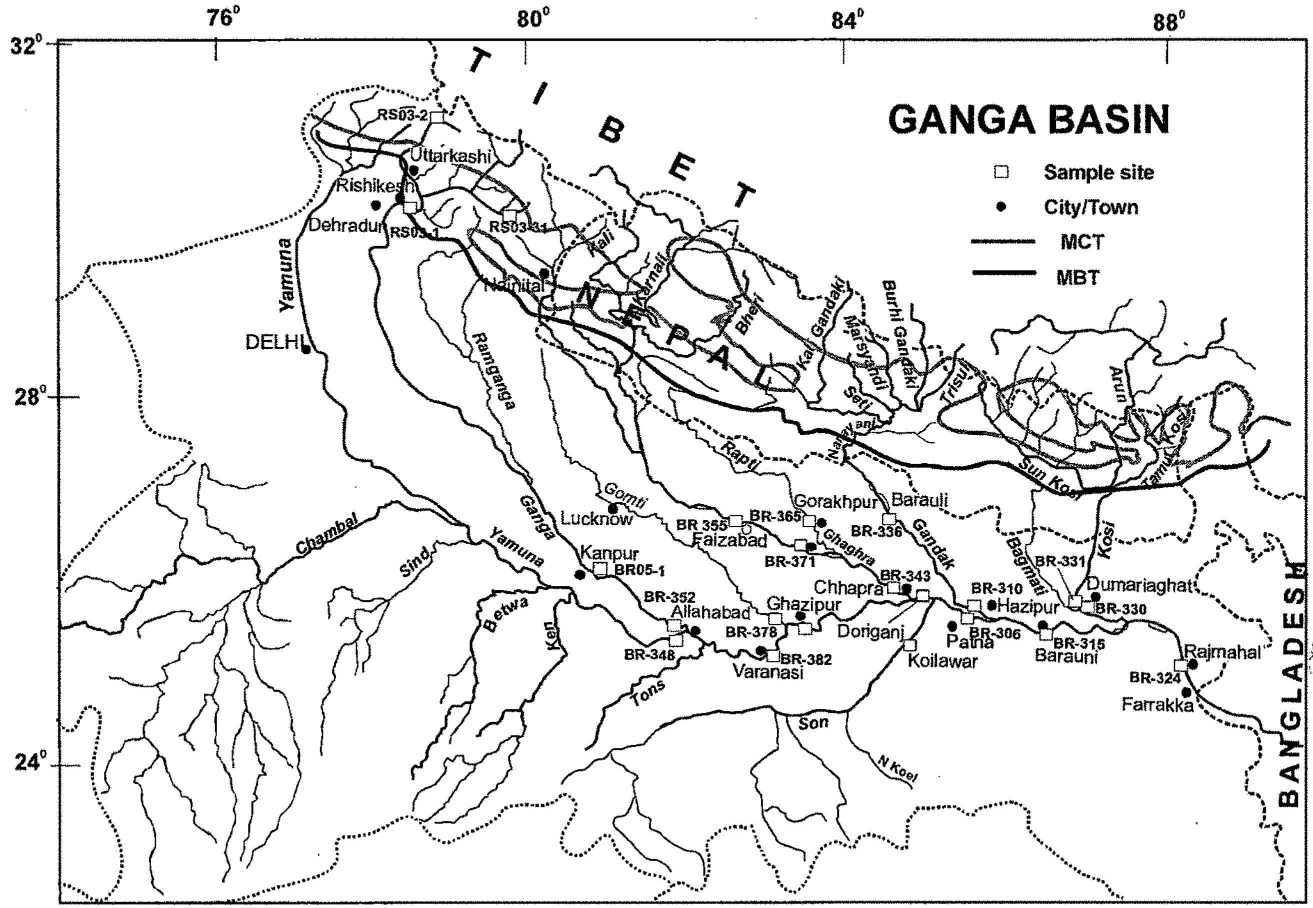

Fig- 3.2: Sampling locations of sediments from the Ganga basin in plain. The locations of samples collected in 2004 are marked in the map. Bank sediments from the Ganga mainstream and its major tributaries were collected all along the course of the Ganga, from its source (Gangotri) to Rajmahal near the Indo-Bangladesh border. Dashed line represents country boundary and dotted line marks the boundary of the Ganga drainage. Main Central Thrust (MCT) and Main Boundary Thrust (MBT) are also marked.

Table 3.1: Sr, Nd, $^{87}Sr/^{86}Sr$ and ε_{Nd} in silicate fraction of bank sediments of the Ganga River System*

Sample	River	Location	Al (%)	Rb $\mu g\ g^{-1}$	$[Sr]_{sil}$ $\mu g\ g^{-1}$	$(^{87}Sr/^{86}Sr)$	[Nd] $\mu g\ g^{-1}$	ε_{Nd} (CHUR)0
Ganga Mainstream								
RS03-3	Bhagirathi	Gangotri	6.3	212	58	0.78793	14	-18.2
RS03-7	Bhagirathi	Uttarkashi	3.9	46	95	0.78159	35	-19.9
RS03-1	Ganga	Rishikesh	5.1	111	78	0.78652	18	-18.1
RS03-1(<4μm)	Ganga	Rishikesh	-	-	72	0.77489	15	-17.4
BR05-1	Ganga	Kanpur	-	-	64	0.77989	-	-
BR352	Ganga	Allahabad	4.2	106	138	0.77726	14	-17.3
BR351 (<4μm)	Ganga	Allahabad	12	-	38	0.77164	33	-15.7
BR06-12-2	Ganga	Allahabad	3.3	73	64	0.77485		
BR382	Ganga	Varanasi	3.5	80	69	0.77137	33	-17.1
BR383(<4μm)	Ganga	Varanasi	11.6	200	44	0.74807	18	-18.8
BR06-14-2	Ganga	Varanasi	3.2	52	63	0.78280	-	-
BR06-10-1	Ganga	Ghazipur	3.2	85	67	0.78089	-	-
BR06-802	Ganga	Doriganj	3.2	72	67	0.78168	-	-
BR306	Ganga	Patna	3.9	86	74	0.76887	35	-21.3
BR06-303	Ganga	Patna	3.4	71	75	0.76830	-	-
BR315	Ganga	Barauni	4.1	100	90	0.75769	21	-19.1
BR314 (<4μm)	Ganga	Barauni	11	84	45	0.75527	24	-16.7
BR06-404	Ganga	Barauni	3.4	70	82	0.76225	-	-
BR324	Ganga	Rajmahal	5	116	92	0.76355	30	-18.1
BR325 (<4μm)	Ganga	Rajmahal	12.4	229	41	0.76179	26	-16.1
BR06-101	Ganga	Rajmahal	4.2	103	102	0.76482		
Alaknanda								
RS03-28	Alaknanda	Birahi Bef. Confl	5.1	121	84	0.75900	33	-17.1
RS03-27	Birahi Ganga	Birahi	2.7	50	48	0.80009	19	-25.5
RS03-31	Pindar	Pindar Valley	4	67	117	0.75379	36	-18.4
Bhagirathi Tributaries								
RS03-9	Syansu Gad		5.7	125	37	0.77909	21	-15.5
RS03-12	Bhilangna	Ghanshyali	5.6	130	69	0.84280	27	-23.3
Tributaries in Plain								
BR348	Yamuna	Allahabad	3.4	72	101	0.76241	10	-17.7
BR06-13-2	Yamuna	Allahabad	3.1	70	88	0.75338	-	-
BR365	Rapti	Gorakhpur	2.7	63	37	0.76148	15	-17
BR364(<4μm)	Rapti	Gorakhpur	12.4	258	41	0.76570	18	-15.9
BR378	Gomti	Before Confl.	4.1	112	81	0.79774	11	-19.4
BR06-11-3	Gomti	Before Confl.	3.2	82	73	0.79276	-	-
BR355	Ghaghra	Ayodhya	3.5	89	67	0.78572	11	-18.9
BR356(<4μm)	Ghaghra	Ayodhya	11.7	278	37	0.77001	20	-17.2

BR371	Ghaghra	Doharighat	3.7	91	76	0.77619	18	-18.5
BR372(<4μm)	Ghaghra	Doharighat	11.8	263	41	0.76787	-	-
BR343	Ghaghra	Revilganj	3.9	89	80	0.77081	17	-18.2
BR344(<4μm)	Ghaghra	Revilganj	10.9	249	50	0.77493	27	-17.4
BR06-905	Ghaghra	Revilganj	3.1	79	66	0.78955	-	-
BR06-205	Son	Koilawar	2.2	82	65	0.77788	-	-
BR336	Gandak	Barauli	4.5	112	105	0.75777	23	-19.1
BR335(<4μm)	Gandak	Barauli	-	-	64	0.76708	26	-18.8
BR310	Gandak	Hazipur	4.2	84	109	0.74738	33	-18.6
BR06-701	Gandak	Hazipur	4.0	87	108	0.74620		
BR330	Kosi	Dumarighat	4.8	114	79	0.80178	16	-18.6
BR331	Kosi	Dumarighat	5.9	129	-	-	34	-19.1
BR331(<4μm)	Kosi	Dumarighat	13.2	305	33	0.80331	24	-18.6
BR06-502	Kosi	Dumarighat	4.3	114	90	0.80369	-	-
BR06-603	Bagmati	Dumarighat	5.5	157	81	0.80237	-	-

* Sr, Nd concentrations and their isotope ratios in silicate fractions. Al, Rb concentrations in bulk samples. Errors in Sr and Nd concentration are <2 % (±2σ) and <20 ppm ((±2σ_μ) for ratios. Confl. : before confluence with mainstream.

3.2.1 Sr, Nd Concentrations and $^{87}Sr/^{86}Sr$ and ε_{Nd} :

The Sr and Nd concentrations and $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios are given in Table-3.1. In the May samples (summer) Sr and Nd in total silicates range from 37 to 138 and 10 to 36 μg g^{-1} respectively. Sr in the October (monsoon) samples collected from the plain range from 63 to 108 μg g^{-1} within the range observed for May samples. The observed range in Sr and Nd concentrations can be due to variability in their source composition, for example Sr in HHC (Higher Himalayan Crystallines) and LH rocks ranges between 4 to 270 and 7 to 166 μg g^{-1} respectively (Mehta et al., 1977; LeFort et al., 1983; Trivedi et al., 1984; Denial et al., 1987; France-Lanord and LeFort, 1988; Stern et al., 1989; Rao et al., 1995; Ahmed et al., 2000; Vijan et al., 2003). Another factor that can contribute to variation in elemental abundances in sediments is their mineralogical composition. This suggestion draws support from the observation that the Al concentration in the sediments analysed averages only 4.4 wt %, (on $CaCO_3$ free basis; chapter-5) a factor of ~2 lower than that in granites and gneisses of the drainage basin (~7%, France-Lanord and Derry, 1997). This can be explained in terms of proportionally higher abundance of Al-poor minerals (e.g., quartz) in these sediments. The impact of such a dilution on Sr and Nd abundances in sediments is difficult to quantify because of large variability in their source concentrations. In spite of the spatial variability in Sr abundance, its concentration in samples from the same location collected during May and October show that on average they are within ±10% of each other (Table-3.2).

Table-3.2: Variability in Sr concentration in samples from the same location collected during May 2004 and October 2006.

Sample	Location	$[Sr]_{ppm}$ 2006	$[Sr]_{ppm}$ 2004	Δ (%)
Ganga	Rajmahal	102	92	11
Ganga	Patna	75	74	1
Ganga	Barauni	82	90	9
Kosi	Dumarighat	90	79	14
Baghmati	Dumarighat	81	79	3
Gandak	Hazipur	108	109	1
Ghaghra	Revil ganj	66	80	18
hazipur	Ghazipur	73	81	10
Yamuna	Allahabad	88	101	13
Ganga	Varanasi	63	69	8
			Mean	9
Δ (%) relative to 2004			(n=10)	

The range in $^{87}Sr/^{86}Sr$ and ε_{Nd} in total silicates of May samples are 0.74738 to 0.84280 and -25.5 to – 15.5, respectively (Table-3.1). The $^{87}Sr/^{86}Sr$ of October samples from the Ganga plain, 0.74620 to 0.80369 (Table-3.1) is nearly within the range of May samples. The average uncertainty as determined from repeat measurements of the same samples is ±0.0005 for $^{87}Sr/^{86}Sr$ (n=5 pairs) and 0.2 ε units for Nd (n=2 pairs) shown in Table-3.3.

These are significantly larger than analytical precision and therefore have to be explained in terms of sample heterogeneity. In order to check if the variability can be due to HCl (0.6 N) leaching procedure, three sediment sample were leached with (5%) acetic acid and the residue analysed for Sr isotopes. The results (Table-3.4) show that the $^{87}Sr/^{86}Sr$ of total silicates separated by acetic acid leach and 0.6N HCl leach agree on average within ±0.00033 (n=3), within the uncertainty of repeat measurements, suggesting that 0.6 N HCl leaching does not measurably alter the $^{87}Sr/^{86}Sr$ of silicates.

Table-3.3 :Repeat measurements for Sr and Nd isotopes

Sample ID	($^{87}Sr/^{86}Sr$)	[Sr] ppm	εNd (CHUR)$_0$	[Nd] ppm	Δ ($^{87}Sr/^{86}Sr$)	Δ (εNd) (CHUR)$_0$
RS03-31	0.75379	117	-18.40	36.0	0.00040	
RS03-31R	0.75419	119				
BR-371	0.77619	76	-18.54	17.7	0.00091	0.12
BR-371R	0.77711	79	-18.42	20.5		
BR-351(<4μm)	0.77164	38	-15.72	32.9	0.00034	0.31
BR-351(<4μm)R	0.77130	40	-16.03	26.6		
BR06-205	0.77788	65			0.00035	
BR06-205R	0.77824	65				
BR06-404	0.76225	82			0.00047	
BR06-404R	0.76272	79				
				Mean	0.00050 (n=5)	0.22 (n=2)

Table-3.4: Effect of acid leaching on $^{87}Sr/^{86}Sr$ in silicates.

	$^{87}Sr/^{86}Sr$ in silicates		
Sample	0.6N HCl	(5%) Acetic Acid	Δ
BR06-101	0.76482	0.76445	0.00037
BR06-13-2	0.75338	0.75304	0.00035
BR06-14-2	0.78280	0.78309	0.00029
		Mean	0.00033

In ten locations in the Ganga plain $^{87}Sr/^{86}Sr$ was measured during both summer and monsoon. The results show that $^{87}Sr/^{86}Sr$ values of silicates sampled during summer and monsoon exhibit measurable differences but without any systematic trend (Table-3.5). The average difference for the 10 locations sampled is ±0.0056 (Table-3.5) much higher than the average uncertainty of repeat measurements (0.0005). This reflects the spatial and temporal heterogeneity in $^{87}Sr/^{86}Sr$ of sediments and therefore provides a more realistic estimate of uncertainty in $^{87}Sr/^{86}Sr$ data. Galy and France-Lanord (2001) reported $^{87}Sr/^{86}Sr$ in three bed-load samples of the Ganga mainstream collected from Rajshahi, Bangladesh. In the two monsoon samples of 1996 and 1998, the $^{87}Sr/^{86}Sr$ values were quite similar, 0.7696 and

0.7691, and in the third sample collected in March 1997 (late winter/ early summer), it was marginally higher, 0.7744. The spread in these three numbers from the same location is 0.0053, within the uncertainty of ±0.0056 derived in this study. More importantly the two monsoon samples, collected two years apart, had quite similar $^{87}Sr/^{86}Sr$. Such estimates for uncertainty in ε_{Nd} values could not be derived as ε_{Nd} measurements were made only during one season, summer.

Table-3.5: Spatial and temporal heterogeneity in $^{87}Sr/^{86}Sr$ of sediments

Sample	Location	$(^{87}Sr/^{86}Sr)_{2006}$	$(^{87}Sr/^{86}Sr)_{2004}$	Δ
Ganga	Rajmahal	0.76482	0.76355	-0.0013
Ganga	Patna	0.76830	0.76887	0.0006
Ganga	Barauni	0.76225	0.75769	-0.0046
Kosi*	Dumarighat	0.80369	0.80178	-0.0019
Gandak*	Hazipur	0.74620	0.74738	0.0012
Ghaghra*	Revil ganj	0.78955	0.77081	-0.0187
Ganga	Allahabad	0.77485	0.77726	0.0024
Yamuna*	Allahabad	0.75338	0.76241	0.0090
Ganga	Varanasi	0.78280	0.77137	-0.0114
Gomti*	Ghazipur	0.792763	0.797743	0.0050
			Mean	0.0056
* Before confluence			(n=10)	

Sr abundance in <4 μm silicates is lower than that in the corresponding total silicates (Table-3.1, Fig-3.3), in contrast to Al (and Nd in majority of samples) which show enrichment in the <4 μm fraction. A cause for the difference in these trends lies in their geochemical behaviour during chemical weathering. Sr, being more mobile, is released to solution, depleting its abundance in the residual solids, whereas Al (Nd), being more resistant to weathering, is retained and enriched in the residue. The depletion of Nd in some of the <4 μm fraction of samples relative to the total (Table-3.1, Fig-3.3) therefore has to be due either to mineral sorting occurring naturally or in the laboratory during size separation or to differences in mixing proportions of end members in total sediments compared to that in their fine fractions. These explanations can also account for the measurable differences in $^{87}Sr/^{86}Sr$ and ε_{Nd} between silicates of total sediments and their <4 μm fractions (Table-3.1).

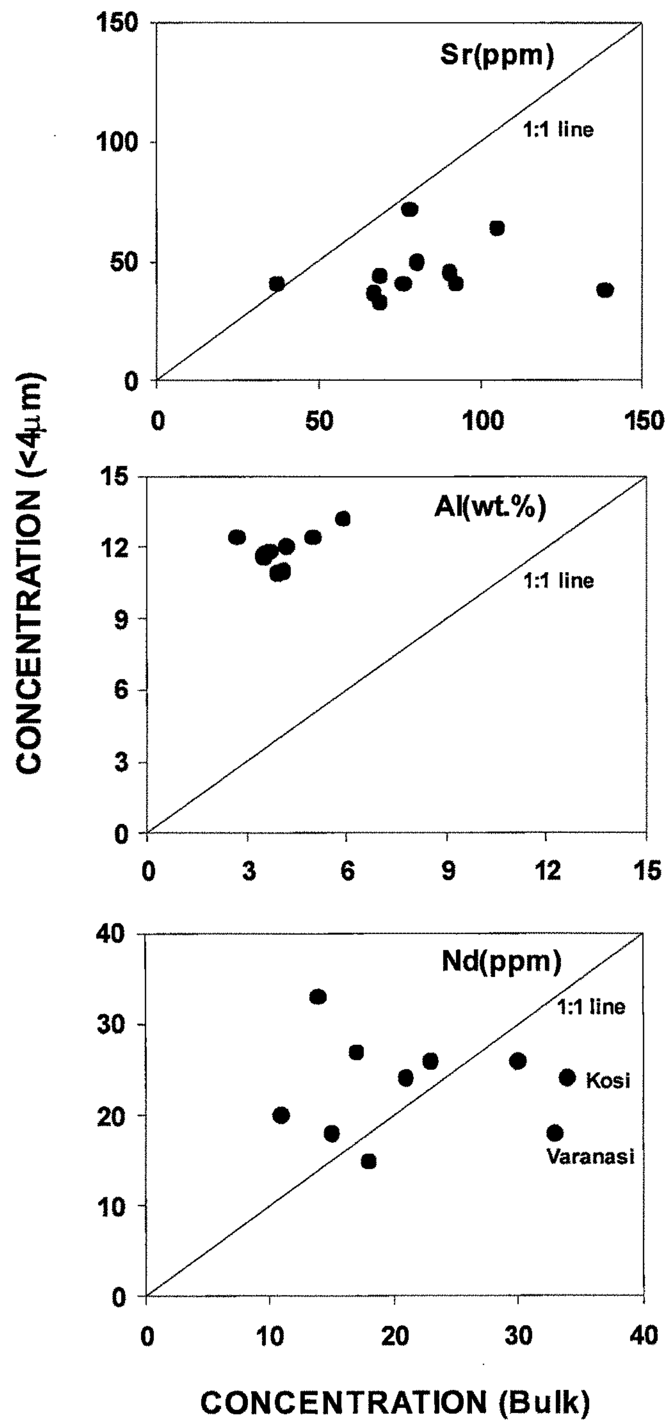

Fig-3.3: Scatter diagram of Sr, Al and Nd abundances in silicates of bulk sediment and their <4 μm fraction. It is seen that Sr in <4 μm fraction is less than that in bulk, whereas Al and Nd (in majority of samples) are enriched in <4 μm fraction.

In spite of these differences, Sr and Nd isotope composition of total silicates would be affected, if at all, only marginally by contributions from <4 μm silicates because their isotopic compositions are not too different, and the latter forms only a minor component of the total sediments.

3.2.2 Sources of Sediments to the Ganga Plain

Potential sources of sediments to the Ganga in the plains are (i) the tectonic units of the Himalaya, the TSS, the Higher Himalaya Cystallines (HHC), the Lesser Himalaya (LH) and the Siwaliks and (ii) peninsular India, through the rivers draining the Deccan Traps, the Vindhyan and the Archean crust. The TSS falls in the rain shadow zone and its occurrence is limited to a small fraction of the drainage area of the headwaters of some of the Himalayan tributaries (the Ghaghra, Gandak and the Kosi). The contribution of sediments from the TSS to the Ganga system, based on mineralogy of Marsyandi sediments (Garzanti et al., 2007) and Nd isotope and fission track studies on sediments from the Trisuli river and the Bengal delta, is found to be minor (4%; Foster and Carter, 2007). The Siwaliks foreland basin sediments are essentially reworked material from the HHC and LH. The observation of Sinha and Friend (1994) that the sediment yield of rivers draining the Siwaliks almost exclusively (for example, the Baghmati) is low indicates that, like the TSS, the Siwaliks are also unlikely to be a significant source of sediments to the Ganga. The sediment yield of the Baghmati river (Sinha and Friend, 1994) if assumed to be typical of the entire Siwaliks range in the Ganga system, indicates that it can account only for <3% of sediment flux to the Ganga. Factors that can contribute to this low sediment contribution are (i) the low relief of the Siwaliks basins which limits the intensity of physical erosion and (ii) the minor fraction of its aerial coverage in the Ganga basin. Campbell et al. (2005) inferred from He-Pb ages of zircons of the Ganga sediments that the contribution from the Siwaliks to the Ganga system is only minor. This makes the HHC and LH the dominant sources of sediments from the Himalaya to the Ganga mainstream. Among the tributaries studied the peninsular drainage supplies sediments only to the Yamuna and the Son, the southern tributaries/sub tributaries of the Ganga. The other two tributaries which also receive peninsular contribution are the Tons and the Punpun, these rivers merge with the Ganga downstream of Allahabad (Fig-3.2). Therefore, the contribution of peninsular drainage to sediments of the Ganga in the plain, needs to be considered only downstream of Allahabad.

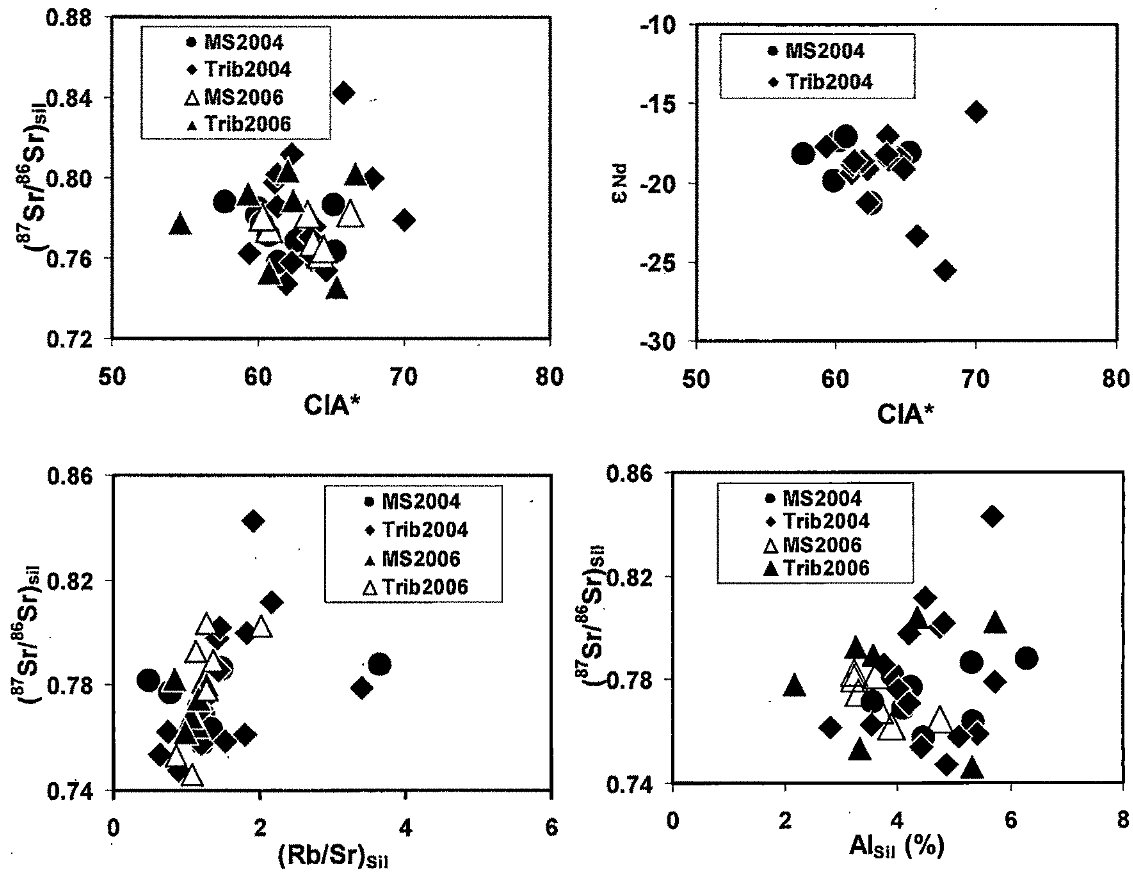

Fig-3.4: Scatter plots of CIA* (Al_2O_3*100/(Al_2O_3+Na_2O+K_2O)) in bank sediments with their $^{87}Sr/^{86}Sr$ and ε_{Nd} values. The bottom two plots are of $^{87}Sr/^{86}Sr$ vs $(Rb/Sr)_{sil}$ and $^{87}Sr/^{86}Sr$ vs Al_{sil}. The measured Al and Rb in the bank sediments are corrected for carbonate to obtain Al_{sil} and $(Rb/Sr)_{sil}$. The data do not show any systematic trend. The scatter is most likely a result of source variability in both CIA*, elemental abundances and isotopic composition. MS: Mainstream, Trib: Tributaries.

The Sr and Nd isotope composition of sediments has been employed to trace the sources of sediments to the Ganga at its outflow in terms of major lithological units and constrain their contributions following similar approaches reported for other regions (Bouquillon et al., 1990; France-Lanord et al., 1993; Galy et al., 1996; Clift et al., 2002; Singh and France-Lanord, 2002; Colin et al., 2006). This approach relies on the assumption that the sediments retain the. Sr and Nd isotopic signatures of their sources. The interrelation of $^{87}Sr/^{86}Sr$ and ε_{Nd} with selected chemical parameters of sediments helps to probe how well this requirement has been met. The intensity of chemical weathering these sediments have undergone, as assessed by comparing their Chemical Index of Alteration (CIA, Nesbitt and Young, 1982) with that of source rocks, suggest that they at best have been subject to minor chemical weathering (see chapter-5). Part of Ca of the sediments of the Ganga is associated with carbonates making it difficult to accurately quantify Ca from silicates. Hence in this study modified Chemical Index of Alteration (CIA*), which does not include Ca, has been used. The modified Chemical Index of Alteration (Colin et al., 1999), given by CIA* (=100*Al_2O_3/(Al_2O_3 + Na_2O + K_2O)) of sediments averages 63±3, overlapping within errors with values of 58±6 for crystallines in the Himalaya, (this work; Chapter-5) 58±7 for LH and 65 for the HHC (France-Lanord and Derry, 1997). The variation of $^{87}Sr/^{86}Sr$ and ε_{Nd} with CIA* and Al_{sil} (Fig-3.4) do not show any systematic trend. Analysis of the Sr isotope data by sub-grouping the samples in terms of summer and monsoon collections from mainstream and tributaries also does not exhibit any common trend with Al and $(Rb/Sr)_{sil}$ (Fig-3.4). Thus, the variations in $^{87}Sr/^{86}Sr$ and ε_{Nd} in sediments can be interpreted in terms of their variability in source composition and their mixing and not due to processes occurring during their transport through rivers. It is however recognized as mentioned earlier that erosion and transport process can modify elemental abundances (e.g. Sr, Al) due to mineralogical sorting, e.g., dilution by mixing with minerals such as quartz.

The Sr and Nd isotope composition of sediments are plotted on a two isotope diagram (Fig-3.5). This figure also includes isotope data for the various end members, HHC, LH, Deccan basalt, Vindhyan sediments and Archean crust (Table-3.6). Among these end members, Deccan Basalts of the peninsular drainage are the least radiogenic in $^{87}Sr/^{86}Sr$ (~0.710) and the most radiogenic in ε_{Nd} (-13 to +5; Table-3.6). The Vindhyan sediments are marginally more radiogenic in Sr compared to the Deccan Basalts but quite depleted in ε_{Nd} (Table- 3.6, Fig-3.5).

Table 3.6: $^{87}Sr/^{86}Sr$ and ε_{Nd} of various litho-units of the Ganga System

Litho units	**$^{87}Sr/^{86}Sr$**		**ε_{Nd}**	
	Range	**Typical**	**Range**	**Typical**
<u>Higher Himalaya</u>				
TSS	0.71-0.73	0.727±0.012	-15 – -12	-13
HHC	0.73-0.79	0.76±0.03	-16.4 – -13.6	-15 ±1.4
<u>Lesser Himalaya</u>				
Pc-carbonates	0.71 -0.85	0.715±0.003	-	-
LH	0.72-0.94	0.85±0.09	-25.3 – -23.5	- .24.4±0.9
<u>Siwaliks</u>	0.72-0.76	0.738±0.018	-19 – -15	- 17.2±1.2
<u>Peninsular Drainage</u>				
Deccan Traps	0.704-0.720	0.71	-13 – +5	-5
Vindhyan	0.72	0.72	-23 – -14	
Archean Craton	0.72-2.55	1.0?	-34 - -50	-50?

Data from (Sarkar et al., 1984; Mahoney, 1988; Derry and France-Lanord, 1996; Peng et al., 1998; Peng and Mahoney, 1995 ; Singh et al., 1998; Galy, 1999; Galy and France-Lanord, 1999; Bickle et al., 2001; Oliver et al., 2003; Saha et al., 2004; Bickle et al., 2005; Chakrabarti et al., 2007; Singh et al., 2008)

For the Archean craton, only very limited data are available (Sarkar et al., 1984, Saha et al., 2004) making it difficult to provide ranges in isotope composition and typical values. The Sr and Nd isotope compositions of total silicates along the course of the Ganga, from Gangotri to Rajmahal, are in the range 0.7577 to 0.7879 and -21 to -15.5 respectively (Table-3.1). Comparison of these $^{87}Sr/^{86}Sr$ and ε_{Nd} values with those reported for the HHC and LH (Table-3.6) suggest that most of the sediment values are closer to the HHC (Fig-3.5). The two samples falling in the LH box (Fig-3.5) are from the Birahi Ganga and the Bhilangna. These two rivers drain the LH almost exclusively. The Sr and Nd isotope mass-balance of the sediments analysed based on two component (HHC and LH) mixing suggests that the Higher Himalayan Crystallines is the dominant contributor to them, accounting for > 65% of the sediments of the Ganga all along its course in the plain (Fig-3.5). A similar conclusion was reached for the Brahmaputra (Singh and France-Lanord, 2002) regarding the source of its sediments. Studies on sediments from the Bay of Bengal (France-Lanord et al., 1990; Galy et al., 1996; Derry and France-Lanord, 1997) also suggest that the HHC makes up most of the silicate sediments in the Bay over the past several million years. Dominance of the HHC in contributing to sediments of the Ganga in its plain is also born out from the studies of U-Pb ages and exhumation rates based on He ages of zircon (Campbell et al., 2005) and Nd and fission track studies of sediments of the Trisuli river in the central Himalaya and the Bengal delta (Foster and Carter, 2007).

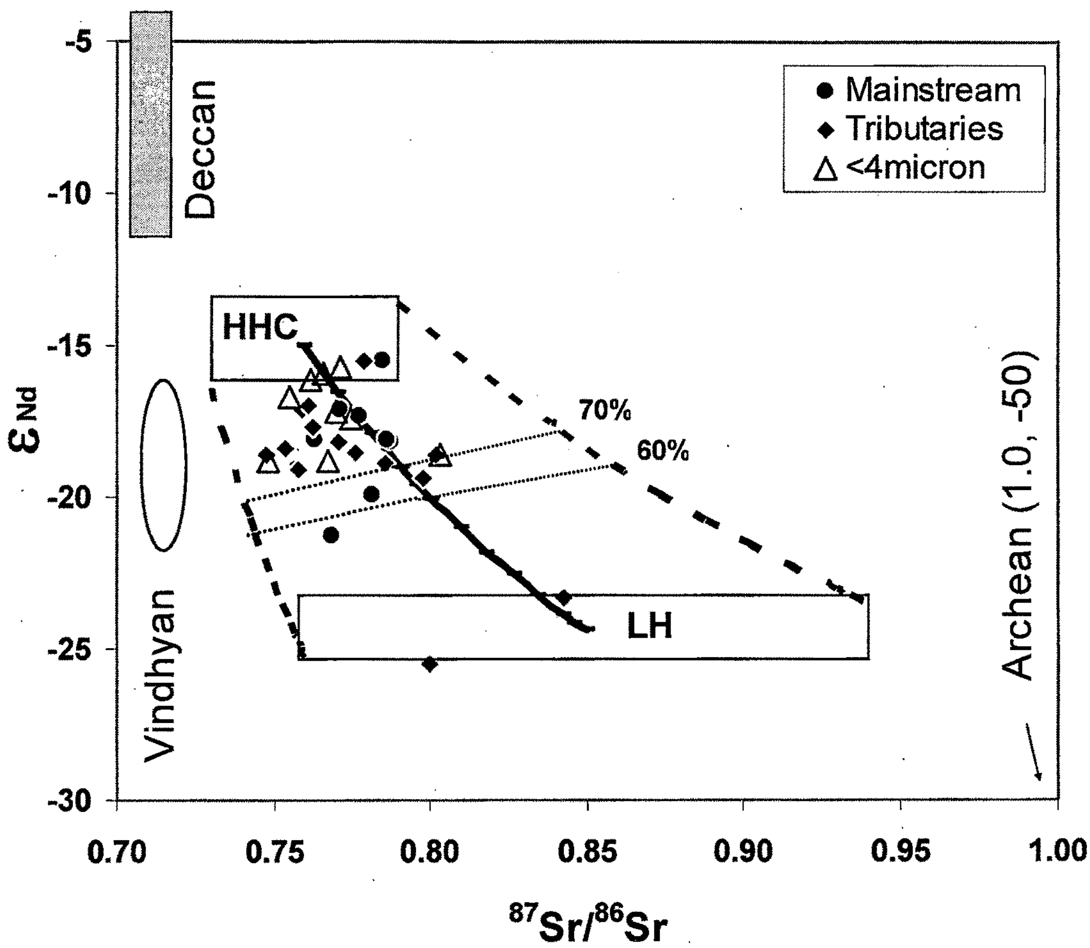

Fig- 3.5: Two isotope system plot, $^{87}Sr/^{86}Sr$ and $\varepsilon_{Nd,}$ in silicates of bulk sediments and their <4 μm fraction. The range in isotopic composition of potential sources of sediments to the Ganga system is also given (see Table-3.6). Plot shows that the isotope ratios of most of the sediment samples cluster below the range of values for the HHC. Also shown is the expected isotopic composition for 70:30 and 60:40, HHC:LH mixtures calculated for typical (solid line) and extreme values (dotted lines) of end members. The data suggest that erosion in the Higher Himalaya accounts for more than 65% of sediments of the Ganga main stream.

The end member values (Fig-3.5) could also lead to the inference that mixing of Deccan Basalts with Archean sources can, in principle generate the measured isotopic composition of the Ganga in the plain. However, such an inference would be incorrect considering that (i) the Deccan and the Archean sources can contribute to the Ganga sediments only downstream of Allahabad and (ii) the contribution of the Deccan Basalts to total silicate of the Ganga at Allahabad can be estimated to be a maximum of ~15% at Varanasi (Fig-3.2) and decreases to a few percent downstream (see later discussions). The Sr isotope composition of the Yamuna sediments at Allahabad, upstream of its confluence with the Ganga, is 0.76241 and 0.75338 for the two seasons sampled (Table-3.1). The Yamuna drains the Higher and the Lesser Himalaya, Deccan and the Vindhyans. The $^{87}Sr/^{86}Sr$ values of the Yamuna sediments are within the range of values for the HHC and close to the lower bound values for the LH, and are significantly more radiogenic than the values for the Deccan Traps and Vindhyans through which many of its tributaries flow (Fig-3.2). These results are an indication of the dominance of the Himalayan sources in contributing sediments to the Yamuna at Allahabad. The ε_{Nd} value of -17.7 for the Allahabad sample (Table-3.1) is significantly more depleted than the lowest value of the Deccan Basalts, consistent with inference based on Sr isotopes that the Himalayan sources dominate the Yamuna sediments. A rough estimate of the peninsular contribution to the Yamuna sediments can be made by assuming that it is a two component mixture of sediments from the Himalayan ($^{87}Sr/^{86}Sr$ of 0.786, same as the Ganga sediments at Rishikesh) and the Deccan/Vindhyan ($^{87}Sr/^{86}Sr$ 0.710) sources with the same Sr concentrations. The estimate (based on equation 3.1, in section 3.2.3) yields values of ~30 and ~40% for the peninsular component in the Yamuna sediment at Allahabad for May 2004. and October 2006, respectively.

The peninsular contribution to the Ganga mainstream at Varanasi is calculated based on the $^{87}Sr/^{86}Sr$ of the Ganga at Kanpur and Varanasi and the Yamuna at Allahabad. This yields a value of 49% for the Yamuna contribution. As the Yamuna at Allahabad has ~30% peninsular component, the Ganga at Varanasi will have ~15% of peninsular contribution. The mainstream sample collected from Allahabad has not been used for this calculation as the location is within the mixing zone of the Ganga and the Yamuna and therefore is not a "pure" Ganga end-member. The Deccan basalt and the Vindhyan components will decrease further downstream and attain value of a few percent at the outflow of the Ganga (see later discussion) as a result of sediment input from other Himalayan tributaries, the Ghaghra, the Gandak and the Kosi (Fig-3.2). These estimates compare with the reported (Wasson, 2003) contribution of ~2.5% sediments from the peninsular drainage to the Ganga system. The contribution from the southern tributaries to the <4 μm silicate fraction is higher at ~35% at Varanasi. Analogous to the total silicates, the contribution to the <4 μm silicate fraction from peninsular drainage also becomes less significant at the Ganga outflow (Rajmahal). Thus, from the above discussions, it is evident that only two sources, the HHC and LH make up most of the silicates in the total sediment load of the Ganga in the plain, with the HHC contributing about two thirds of the total.

3.2.3 Estimation of sediment contribution from sub-basins to the Ganga mainstream

The spatial trend of $^{87}Sr/^{86}Sr$ along the mainstream Ganga (Fig-3.6 & 3.7) is quite similar during both May and October sampling. These results, along with Sr isotope composition of tributary sediments, can yield estimates of their mixing proportions with sediments of the Ganga mainstream, provided the isotopic composition of the mixing end members is distinctly different, and outside the average uncertainties. In this work for $^{87}Sr/^{86}Sr$, the average difference in two season sampling from ten locations, ±0.0056 (Table-3.5) has been used as the uncertainty in the end member values. The $^{87}Sr/^{86}Sr$ of the Ganga at Varanasi (0.77137) and the Ghaghra at Revilganj (0.77081) for the 2004 sampling, and the Ganga at Ghazipur (0.78089), the Ghaghra at Revilganj (0.78955), the Ganga at Doriganj (0.78168) and the Son at Koilawar (0.77788) for the 2006 sampling, fall within this uncertainty. This precludes the estimation of mixing proportion of the Ghaghra and the Son sediments with that of the Ganga mainstream.

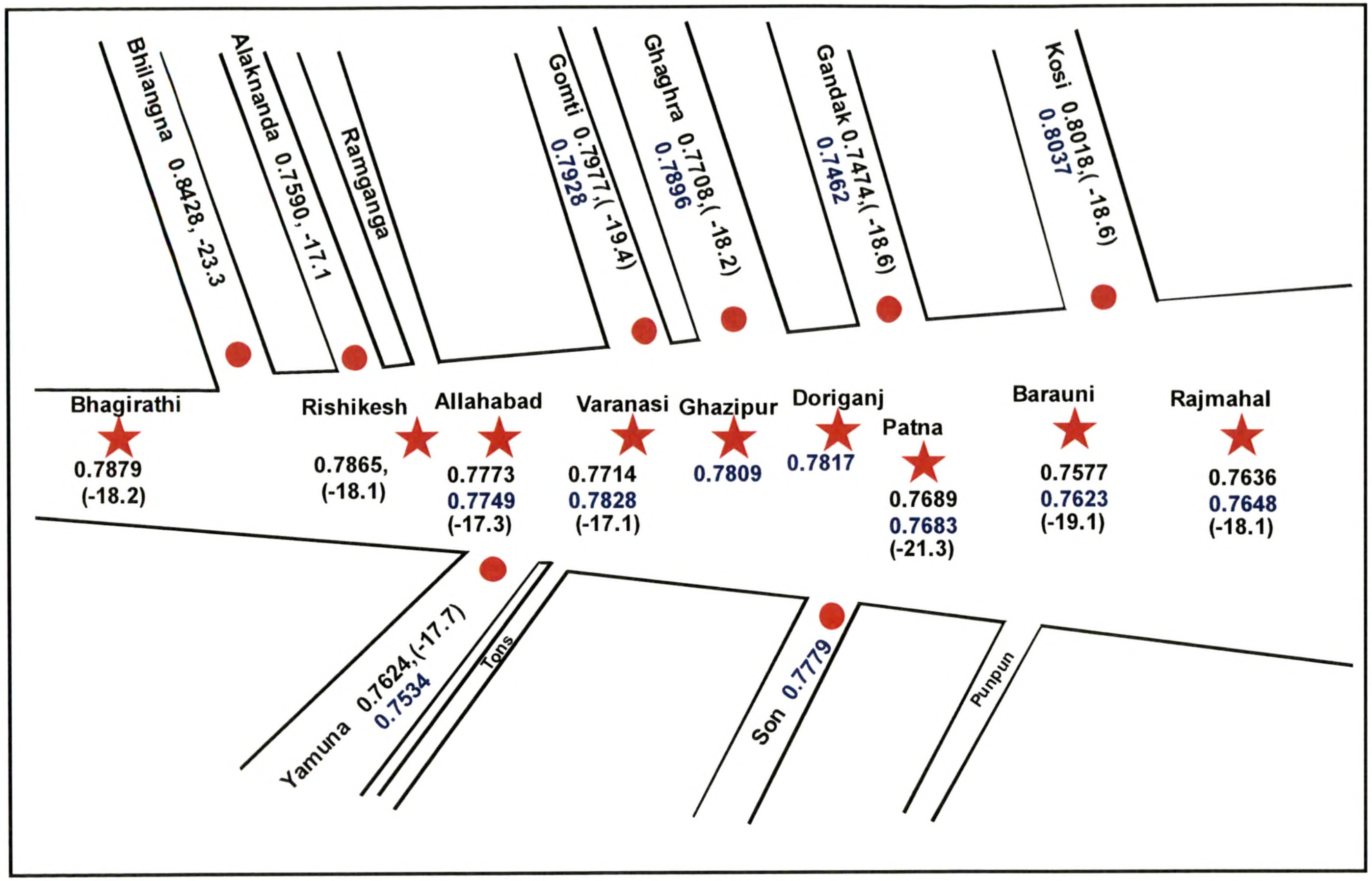

Fig-3.6: Funnel diagram (not to scale) of the Ganga mainstream and its tributaries along with $^{87}Sr/^{86}Sr$ for May 2003, 2004 and October, 2006 (values given in blue colour) and ε_{Nd} (May 2003, 2004; in parenthesis) in silicates of their bulk sediments. These data coupled with a two end member mixing model has been used to estimate the fractional contributions of sediments to the Ganga from the Gandak, the Kosi and Ganga sub-basins upstream Patna.

The $^{87}Sr/^{86}Sr$ of the Ganga mainstream sediments shows a sharp decrease at Barauni (Fig-3.6 & 3.7) during both May and October after the confluence of the Gandak. During both these seasons, the lowest $^{87}Sr/^{86}Sr$ value in the Ganga mainstream is observed at Barauni as a result of mixing with relatively less radiogenic Sr from the Gandak sediments. The $^{87}Sr/^{86}Sr$ of the Gandak at Hazipur upstream of its confluence with the Ganga is 0.7474 and 0.7462 for May 2004 and Oct 2006 respectively. Another sample of the Gandak sediments collected from Barauli ~100 km upstream of Hazipur has $^{87}Sr/^{86}Sr$ of 0.7578. All the three $^{87}Sr/^{86}Sr$ values of the Gandak sediments are less radiogenic than those of the other Himalayan tributaries, the Ghaghra and the Kosi, both of which have $^{87}Sr/^{86}Sr \geq 0.77$ (Table-3.1, Fig-3.6). The lower $^{87}Sr/^{86}Sr$ of the Gandak compared to the Ghaghra and the Kosi could be due either to spatial variability in $^{87}Sr/^{86}Sr$ of HHC or to relatively higher contribution from TSS to the sediments of the Gandak (Galy, 1999). Considering that Hazipur is close to the mouth of the Gandak (Fig-3.2), the $^{87}Sr/^{86}Sr$ of samples from this location is taken to be representative of the Gandak sediments discharging into the Ganga for calculating mixing proportions. After mixing with the Gandak sediments, the $^{87}Sr/^{86}Sr$ of the Ganga mainstream sediments drops from 0.77137 (Varanasi) to 0.75769 in May and 0.78168 (Doriganj) to 0.76225 in October. This drop is a few times the uncertainty in the end member values (±0.0056) and orders of magnitude higher than the precision of repeat measurements. These results suggest that the sediment budget of the Ganga is influenced significantly by the contribution from the Gandak. The impact of the Gandak contribution on the $^{87}Sr/^{86}Sr$ of the Ganga mainstream is discernible even in the sample from Patna, as this sample falls within the mixing zone of the Gandak, particularly during high flow. Further downstream, the $^{87}Sr/^{86}Sr$ of the Ganga sediment increases to 0.76355 (summer) and 0.76482 (monsoon) at Rajmahal, due to mixing with more radiogenic Sr sediments from the Kosi (Figs-3.6 & 3.7).

The $^{87}Sr/^{86}Sr$ of <4 µm silicate fraction follows the trend of the total silicates (Fig-3.6), but it shows a sharp decrease, from 0.77164 at Allahabad to 0.74807 at Varanasi. This is due to supply of Yamuna sediments rich in fine fraction and low in $^{87}Sr/^{86}Sr$. The difference in $^{87}Sr/^{86}Sr$ between the total and

<4 μm silicate fraction is maximum at Varanasi. Further downstream the Sr isotope composition of the <4 μm silicate fraction converges with that of the total. The ε_{Nd} of total sediment silicates of the Ganga also varies along its course within a narrow range (Fig-3.8).

The ε_{Nd} at Rishikesh is -18.1 which increases to -17.3 at Allahabad and decreases to its lowest value of -21.3 at Patna. This can be interpreted in terms of supply from the Son catchment which has exposures of Archean basement.

Table-3.7 Estimation of fraction of sediment contribution from tributaries to the Ganga mainstream

	Location	End Members	($^{87}Sr/^{86}Sr$) End members	($^{87}Sr/^{86}Sr$) Mixture	% contribution
Summer 2004					
Ganga	VARANASI	1. Yamuna@Allahabad	0.762	Ganga@ Varanasi	49
		2. Ganga@ Kanpur	0.780	0.771	51
	BARAUNI	1. Gandak@ hazipur	0.747	Ganga@Barauni	51
		2. Ganga@ Patna	0.769	0.758	49
	RAJMAHAL	1. Kosi@Dumariaghat	0.802	Ganga@Rajmahal	13
		2. Ganga@ Barauni	0.758	0.764	87
Yamuna	ALLAHABAD	1. Vindhyan/Deccan	0.705	Yamuna@Allahabad	30
		2. Himalayan	0.787	0.762	70
Post Monsoon 2006					
	BARAUNI	1. Gandak@ hazipur	0.746	Ganga@Barauni	55
		2. Ganga@ Doriganj	0.782	0.762	45
(<4μm Fraction)					
	VARANASI	1. Vindhyan/Deccan	0.705	Ganga@Varanasi	38
		2. Himalayan component	0.775	0.748	62

The Son contribution, however, does not influence the $^{87}Sr/^{86}Sr$ of the Ganga mainstream sediments as their $^{87}Sr/^{86}Sr$ values are similar (Table-3.1). Based on ε_{Nd} of Ganga sediments from Varanasi and Patna and assuming ε_{Nd} of ~ -50 for the Son, its sediment contribution to the Ganga at Patna can be estimated to be ~15%. Further downstream there is a steady increase of ε_{Nd}

due to inputs from the Gandak and the Kosi. The ε_{Nd} values of the <4 μm silicate fraction (Fig-3.8) track the trend of the total silicates.

The spatial variability in physical erosion rates among the three sub-basins of the Ganga upstream of Patna (comprising the basins of the Alaknanda, Bhagirathi, Yamuna and the Ghaghra), the Gandak and the Kosi has been assessed by evaluating the sediment budget of the Ganga mainstream (downstream of Patna) based on a two end member mixing model (for example, for the Ganga at Rishikesh, the two end members are the Bhagirathi and the Alakananda; for the Ganga at Rajmahal, the end members are the Ganga at Barauni and the Kosi).The mixing proportions are calculated (France-Lanord et al., 1993; Galy et al., 1996; Singh and France-Lanord, 2002) based on the measured isotope ratios of appropriate end members of Ganga mainstream and tributary sediments and assuming uniform Sr concentrations. Fraction of sediment contribution from different sub-basin to the Ganga mainstream has been estimated using mass balance relation. For example, the fractions of sediment at Barauni from the Gandak and Ganga mainstream upstream Doriganj were estimated using following relation:

$$f_{Gandak} = \frac{\left[\left\{\left(\frac{Sr}{Al}\right)_{GB} * R_{GB}\right\} - \left\{\left(\frac{Sr}{Al}\right)_{GD} * R_{GD}\right\}\right]}{\left[\left\{\left(\frac{Sr}{Al}\right)_{GH} * R_{GH}\right\} - \left\{\left(\frac{Sr}{Al}\right)_{GD} * R_{GD}\right\}\right]} \quad \text{.................} \quad (3.1)$$

Where, f_{Gandak}: fraction of sediment contributed from Gandak to the Ganga mainstream at Barauni.

$\left(\frac{Sr}{Al}\right)$: concentration ratio of Sr and Al and $R = \frac{^{87}Sr}{^{86}Sr}$

GB: Ganga at Baurauni, GD: Ganga at Doriganj, GH: Gandak at Hazipur.

It has been assumed that $\frac{Sr}{Al}$ in the sediments of all the end members are same and hence equation reduces to

$$f_{Gandak} = \frac{(R_{GB} - R_{GD})}{(R_{GH} - R_{GD})} \quad \text{.................} \quad (3.2)$$

An uncertainty of ±0.0056 on $\frac{^{87}Sr}{^{86}Sr}$ of each of these end members are propagated in equation (3.2) to get the uncertainty in the estimated fraction.

Fraction of contribution of sediments from rest of the Ganga upstream Doriganj

$$= 1 - f_{Gandak} \quad \text{................ (3.3)}$$

Similar calculation has been done at Rajmahal between Ganga at Barauni and Kosi. Data of two season samplings have been used separately.

In this study, estimates of mixing proportion rely more on $^{87}Sr/^{86}Sr$ data as the range in $^{87}Sr/^{86}Sr$ of the sediments is much wider compared to ε_{Nd} (Table-3.1). The results of these calculations (Table-3.7 & 3.8) suggest that the contributions of sediments to the Ganga in the plain from the three sub-basins differ significantly, with the Gandak sub-basin dominating the sediment budget. This sub-basin supplies about 45 and 51 % of total sediments of the Ganga at Rajmahal during the 2004 and 2006 sampling respectively. The contribution of the Gandak in the 2004 sample is calculated using the $^{87}Sr/^{86}Sr$ data of the Ganga at Patna and Barauni and the Gandak at Hazipur. This can be an underestimate as sediments of the Ganga at Patna may have some contribution from the Gandak. For the 2006 sampling, it is based on data from the Ganga at Doriganj and Barauni and the Gandak at Hazipur. (The Gandak proportion changes to 37% and 54% for the 2004 and 2006 sampling if the calculations employ both $^{87}Sr/^{86}Sr$ and Sr concentration, the latter expressed in terms of Sr/Al). The Ganga sub-basin upstream of Patna (comprising of the Bhagirathi, Alaknanda, Yamuna, and the Ghaghra, Fig-3.2) and the Kosi contribute about 43 and 6-13 % respectively to the sediment budget of the Ganga. The sediment contribution from the Kosi increases to ~18% if the $^{87}Sr/^{86}Sr$ of the Ganga bed-load at Rajshahi, Bangladesh (Galy and France-Lanord, 2001) is used as the end member for calculation. Attempts to estimate the mixing proportions based on ε_{Nd} have not been very rewarding. The ε_{Nd} values of the Ganga mainstream samples have a limited range, -18±1, the only exception being the Patna sample which has a value of -21.3 (Table-3.1).

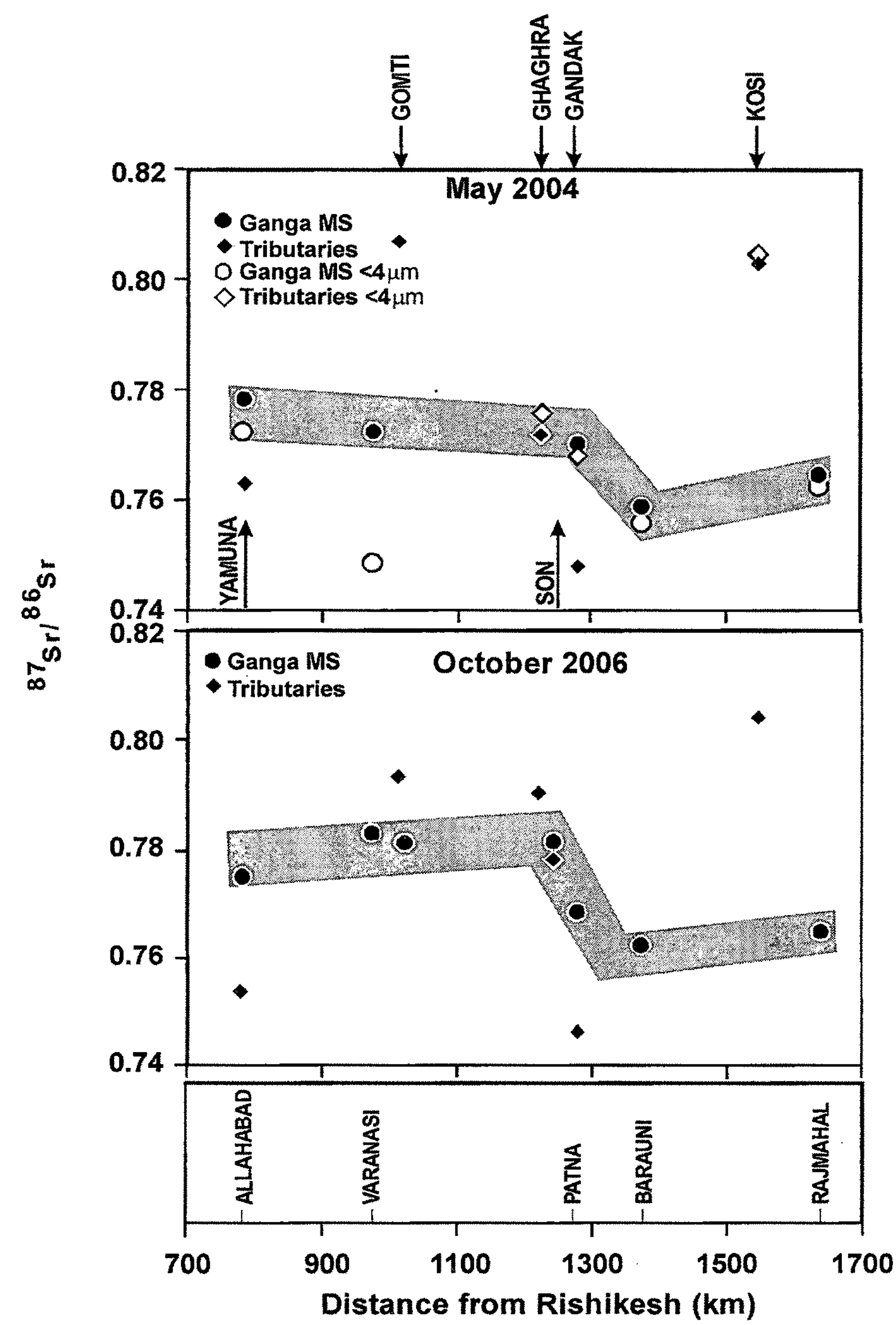

Fig-3.7; Downstream variations in $^{87}Sr/^{86}Sr$ values of silicates of the Ganga sediments during May 2004 and Oct 2006. During both the sampling periods, $^{87}Sr/^{86}Sr$ of the Ganga mainstream sediments decrease sharply at Barauni after the confluence with the Gandak and then increase marginally at Rajmahal after mixing with more radiogenic sediments of the Kosi. Sharp and consistent decrease in $^{87}Sr/^{86}Sr$ during both the summer and the monsoon seasons at Barauni bring out the impact of the Gandak contribution to the sediment budget of the Ganga. Gray band denotes the $^{87}Sr/^{86}Sr$ spatial evolution of Ganga sediments downstream Allahabad.

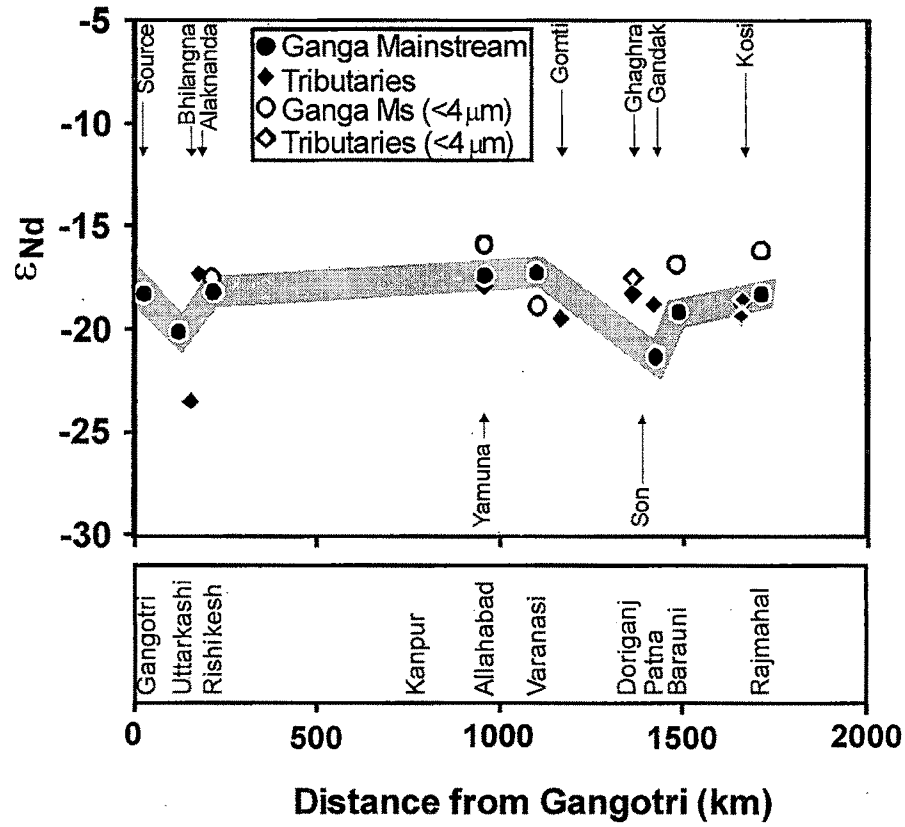

Fig-3.8: Downstream variation in ε_{Nd} of the Ganga mainstream sediments. Analogous to $^{87}Sr/^{86}Sr$, the downstream variations of ε_{Nd} is due to mixing of sediments from the Ganga mainstream with sediments of its tributaries.

Among the tributaries, other than for the Birahi Ganga and the Bhilangna, all the others also have ε_{Nd} values in same range as the Ganga mainstream, -18±1. This narrow range coupled with additional uncertainties that can arise from temporal variability makes it difficult to obtain reliable estimates of mixing proportions from the ε_{Nd} data. In spite of this, analyses of ε_{Nd} summer data show the dominance of the Gandak contribution to the sediment budget of the Ganga in the plain. The ε_{Nd} mass balance yields a value of ~80% for the Gandak component during summer.

3.2.4 Spatial Variability in Erosion Rate

Spatial variability in erosion in the Ganga basin has been determined from the available data on total sediment flux from the Ganga and the fractional contribution from the various sub-basins as derived based on

$^{87}Sr/^{86}Sr$. Estimates of suspended load supply from the Ganga at Farakka range from 500 to 700 million tons yr^{-1} (Hay, 1998; Islam et al., 1999). Recently, Galy and France-Lanord (2001), using Si, Al and Fe budgets of sediments, estimated that the bedload/flood plain sequestration can be a major component of sediment flux and that the total sediment flux from the Ganga could be as high as ~1000 million tons yr^{-1}. This value has been used in the following calculations of erosion rates. Further, the impact, if any, of aggradation and degradation of the Ganga plain (Jain and Sinha, 2003) has not been considered in the erosion rate calculations.

The sediment yield for the three sub-basins of the Ganga has been calculated based on relation 3.4.

$$R_{Erosion} = \left(\frac{F_t . f_{trib}}{A_{trib}} \right) \qquad \text{..........................} \quad (3.4)$$

F_t is the total sediment flux (=1000 million tons yr^{-1}), f_{trib} is the fractional sediment contribution for tributary/sub basin, A_{trib} is the drainage area of the tributary/sub basin.

The fractional tributary contributions are 45 and 51 % from the Gandak, 13 and 6 % from the Kosi and the balance from Ganga upstream of Patna. The calculated specific erosion rates vary from ~1200 to 16000, tons $km^{-2} yr^{-1}$ (Table-3.8). The specific erosion rate can be translated to linear (cm yr^{-1}) using average density (2.5 g cm^{-3}) of sediments. These values range from ~0.5 to ~6 mm yr^{-1} in the Himalayan sector of the drainage assuming that all sediments is of Himalayan origin (Table-3.8). The estimates of sediment contributions by these three sub-basins are disproportionate to their aerial coverage in the Ganga drainage, as the Gandak occupies only ~5% of the total area, the Kosi ~8% and the Ganga upstream of Patna ~ 80% (Table-3.8). The results yield a wide range of specific sediment discharge (sediment flux normalised to drainage area) for the three sub-basins suggesting significant variation in physical erosion rates among them.

Table 3.8: Estimates of Sediment fraction and erosion rates of various sub-basins of the Ganga*

Rivers sub-basin	Area		Discharge[a]	Runoff	Sediment		Sediment Yield		Physical erosion rate (mm yr^{-1})			
	Himalayan	Total			Fraction (%)		tons $km^{-2} yr^{-1}$		Total Area		Him. Area	
	(km^2)		$10^6 m^3 yr^{-1}$	m yr^{-1}	2004	2006	2004	2006	2004	2006	2004	2006
Gandak	31753	46300	49385	1.6	45	51	14200	16100	3.9	4.4	5.7	6.4
Kosi	51440	74500	48155	0.9	13	6	2500	1200	0.7	0.3	1.0	0.5
Ganga upstream Patna (GA+RG+YAM+ GH)	91537	794100	107884	1.2	42	43	4600	4700	0.2	0.2	1.8	1.9

GA: Ganga; RG: Ramganga; YAM: Yamuna; GH: Ghaghra

* Area, discharge data from [Galy, 1999; Rao, 1975], [a] at foothills of the Himalaya

Further, among the three sub-basins the Gandak in the Himalaya has the highest erosion rate, ~ 6 mm yr^{-1} and the Kosi the lowest, ≤1 mm yr^{-1} (Table-3.8). The sediment fluxes of the Gandak and the Kosi for the two seasons range from 450 to 510 and 60-130 million tons yr^{-1} respectively. Sinha and Friend (1994) reported that the contribution of the Gandak to the particulate matter flux of the Ganga at Farakka is a factor of two higher compared to that of the Kosi. This trend in the sediment fluxes (Gandak and Kosi) is consistent with that observed in this study, however the range in fluxes differs significantly.

3.2.5 Uncertainty in estimation of sediment fraction and in erosion rate

The estimated sediment fluxes and erosion rates of the individual sub-basins are subject to uncertainties arising from errors in the total sediment fluxes and variability in isotope composition of sediments. The former though will not affect the calculated relative fluxes and erosion rates among the various sub-basins (Table-3.8), it is a source of error in the determination of their absolute values. This in turn can impact on the inferences drawn from inter-comparison of results from this study with those based on other methods for the Ganga basin and for the other river basins (e.g. Brahmaputra, Indus). The uncertainty in isotope composition of end members is another factor determining error in fluxes and erosion rates of sub-basins. In this study, as mentioned earlier, the measured average difference of the two season sampling (±0.0056) is assumed as the uncertainty in $^{87}Sr/^{86}Sr$. Propagation of this error in $^{87}Sr/^{86}Sr$ yields in an uncertainty of 54% in the contribution of sediments from the Gandak and the rest of the basin upstream of Doriganj for monsoon samples. Based on this, the contribution from the Gandak is estimated to be 51±27% and 43±23% for the Ganga basin upstream of Doriganj. A 50% uncertainty in the sediment fraction estimates translates to similar fractional uncertainty on the erosion rates of various sub-basins, for example, considering the uncertainty in the sediment fraction, the erosion rates in the Gandak sub-basin will be ~6±3 mm yr^{-1}. It may be possible to reduce the uncertainties in the erosion rate estimates through time-series sampling over long periods. In summary, the estimates of sediment flux from the Gandak based on two season sampling spread over about two years are quite consistent. This suggests that, despite the larger uncertainty in the estimated sediment fraction, the sediment budget of the Ganga River is dominated by contribution from the Gandak. It is also recognized that the absolute value of total sediment flux from the Ganga and its associated uncertainties are key factors determining the accuracy and precision of erosion rate estimates.

The occurrence of alluvial fans formed by the tributaries upstream of their confluence with the mainstream is another factor that can introduce uncertainties in their estimated sediment contribution. The Ghaghra, the Gandak and the Kosi all form large fans in the Gangetic plain (Gupta, 1997). The role of these fans in determining the sediment contribution of these rivers to the Ganga is not well established. It is suggested that among these, the Gandak and the Kosi fans store sediments causing aggradation (Sinha, 2005), with the Gandak having a larger fan area (Gupta, 1997; Shukla et al., 2001; Goodbred Jr., 2003).

Another concern is the impact, if any, of flash floods or transient events in a particular tributary which can supply enormous amount of sediments in a short time span and thereby can significantly influence the sediment budget of the Ganga mainstream. The observation that the trend of $^{87}Sr/^{86}Sr$ along the mainstream Ganga (Fig-3.7) is very similar for samples collected nearly two years apart and during different seasons, leads to the inference that such transient events were unimportant during the period of study.

3.2.6 Comparison with available erosion rates over the Himalaya

Different approaches have been used to determine erosion rates of river basins. The time interval over which the deduced erosion rates are applicable depends on the approach, for example cosmic ray produced isotopes typically yield average rates over 100 to 10000 years, fission tracks are applicable for time intervals in the range of 0.1 to 1 million yr whereas flux measurements of sediments and their components (e.g., Sr, Nd isotopes, mineralogy) represents contemporary erosion rates. Therefore, while comparing erosion rates derived from different approaches, the time scales over which they are applicable has to be borne in mind.

The erosion rate estimated in this study for the Gandak basin (6±3 mm yr^{-1}) falls within the range of values 3-13 mm yr^{-1} reported for the Marsyandi basin (Table-3.9), one of its major headwater tributaries (Fig-3.2), based on fission track, ^{14}C and mineralogical studies (Table-3.9; Burbank et al., 2003; Garzanti et al., 2007; Pratt-Sitaula et al., 2007). The erosion rates of the Gandak, based on its suspended load abundance, are between 1.4-5 mm yr^{-1}. Sinha and Friend, (1994) reported a suspended load flux of 82 million tons yr^{-1} for the Gandak at Dumarighat for the 10 year period, 1980-89. This would correspond to a total sediment flux of ~160 million tons yr^{-1}, considering bed load and suspended load fluxes to be equal (Galy, 1999; Garzanti et al., 2007). Assuming that this sediment flux is derived entirely from the Himalayan region, this would yield an erosion rate of 2 mm yr^{-1}. Garzanti et al. (2007) reported an erosion rate of 1.4 mm yr^{-1} for the Gandak basin in the Himalaya, based on a total sediment flux of ~121 million tons yr^{-1} sourced from a feasibility study report (Hydroelectric power development project, 1982). A compilation of the sediment yield of global rivers [http://www.fao.org/ag/aGL/aglw/sediment/default.asp] reports a value of 6000 tons km^{-2} yr^{-1} for the Gandak basin based on the work of Kansakar and Acharya (1990). This sediment yield, when adjusted to include bed load, gives an erosion rate of ~5 mm yr^{-1}. The sediment flux for the Kosi determined in this study ranges between 60 and 130 million tons yr^{-1}. This compares with values of 86-360 million tons yr^{-1} of total sediment flux (calculated from Jain and Sinha (2003), Sinha and Friend (1994) and ~160 million tons yr^{-1} calculated from the data for the rivers Arun, Sun Kosi and Tamur (http://www.fao.org/ag/agl/aglw/sediment/). These comparisons show that the sediment flux and erosion rates determined in this study are within the broad range of reported values.

Lave and Avouac (2001) reported spatial variability in erosion rates for the rivers draining the Nepal Himalaya based on a model considering various parameters such as distribution of terraces in river channels, the present geometry of rivers and the shear stress exerted by flowing water.

Table 3.9: Erosion rates over the Himalaya determined by various techniques

Sl.	Area/ Location	Technique	Erosion Rate (mm yr^{-1})	Reference	Time Scale
Ganga Basin					
1	Marsyandi Basin	Sand petrography and mineralogy	1.6 - 5.2	Garzanti et al., 2007	present day
2	Marsyandi Basin	Apatite Fission Track (AFT)	2 – 5	Burbank et al., 2003	Million year
3	Marsyandi Basin	^{14}C Method, river depth	~13	Pratt-Sitaula et al., 2007	5 ky
4	Marsyandi and Nyadi catchment	Fission track	~3.1	Huntington et al., 2006	0.5-9 My
5	Gandak basin in Himalaya	Isotopic study of Bed Sediments	6	This study	present day
6	Kosi Basin in Himalaya	Isotopic study of Bed Sediments	0.5 - 1	This study	present day
7	Ganga upsream Patna (Himalayan Drainage)	Isotopic study of Bed Sediments	2	This study	present day
Brahmaputra Basin					
8	Eastern Syntaxis in Himalaya (Brahmaputra)	Isotopic study of Bed Sediments	~14	Singh, 2006	present day
9	The Namche Barwa (Eastern syntaxis)	Isotopic and fission track dating	~10	Burg et al., 1998	Million year
Indus Basin					
10	Indus River Nanga Parbat (Western Himalaya)	cosmogenic nuclides (^{10}Be and ^{26}Al)	10 – 12	Leland et al., 1998	present day
11	Western Syntaxis	Fission Track	2 - 12	Burbank et al., 1996	Million year

Their results show that erosion in the Higher Himalaya is significantly higher compared to that of the Lesser Himalaya, consistent with that inferred from this study. Further, their study also showed that the Kali Gandaki, the Marsyandi, the Buri, the Trishuli (headwaters of the Gandak) and the Arun and the Sun Kosi (headwaters of the Kosi) (Fig-3.2) all have similar erosion rates in the Higher Himalaya. This result differs from that of the present study which suggests that the Gandak sub-basin erodes at a higher rate than that of the Kosi. The causes for the inconsistency between the two approaches are unclear but could be a result of difference in spatial and temporal scales and uncertainties in various model parameters. For example, this study estimates the erosion rate over the entire sub-basin, whereas the model calculations present the rate of incision of the rivers.

Erosion rates in the Himalayan drainage of the Kosi and the Ganga (upstream of Patna/Doriganj), estimated in this study, are 0.5 to 2 mm yr^{-1} respectively (Table-3.8), similar to both short and long term 'typical erosion rates' for the Himalayan range, such as the Alaknanda basin of the Ganga (Table-3.9; Vance et al., 2003) and the Jia Bhareli and Manas basins of the Brahmaputra (Table-3.9; Singh, 2006).

Table-3.10: Hotspot contribution to global riverine sediment budget

Hot spots of the Himalaya	Sediment flux (million tons yr^{-1})	Area (km^2)	Reference
Eastern Syntaxis	900	26000	Singh, 2006
Gandak (Himalayan drainage)	480	31800	This work, Singh et al., 2008
Western Syntaxis	137	12600	Garzanti et al., 2005
Total	**1517**	**70400**	
World Riverine Sediment flux	20000	100x10^6	Hay et al., 1998; Holland (1978, 1981).

Contribution of Hotspots to sediment generation = ~7-8 (%)
Area of Hotspots in world surface area = 0.07 (%)

The erosion rate for the Himalayan drainage of the Gandak, ~6 mm yr^{-1} (Table-3.9), though highest among the Ganga sub-basins, is lower than both long and short term erosion rates reported for the syntaxes of the Himalaya (Burg et al., 1998; Leland et al., 1998; Singh, 2006). The erosion rates over the Ganga system determined in this study coupled with those reported for the Brahmaputra (Burg et al., 1998; Finlayson et al., 2002) and the Indus (Leland et al., 1998) systems suggest that typical erosion rates over the Himalaya (combined Higher and Lesser Himalaya) are ~1-3 mm yr^{-1} . A few hot spots such as the syntaxes and the Gandak sub-basin have significantly higher erosion rates, in the range of ~6 to ~14 mm yr^{-1}.

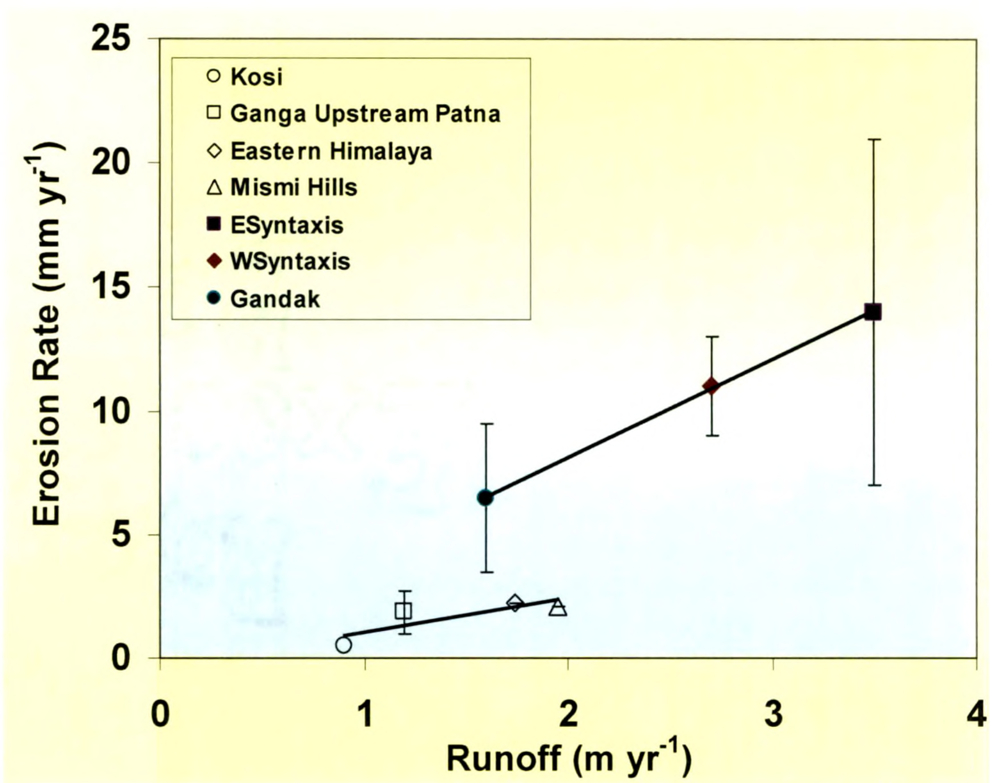

Fig-3.9: Physical erosion rates in the Ganga-Brahmaputra-Indus basins as a function of run off. Two trends are seen, one with gentler slope, for rivers with lower precipitation and lower relief and other for those with higher precipitation and higher relief. Data for the Kosi, Ganga (upstream of Patna) and the Gandak are from this study, others from (Leland et al., 1998; Singh, 2006). The erosion rate for western syntaxis is a long term average (Leland et al., 1998) whereas for the other basins it is present day value.

These hotspots determine the sediment fluxes of the Ganga – Brahmaputra - Indus river basins and therefore the sediment budget of the Bay of

Bengal and the Arabian Sea (Stewart and Hallet 2004). These three hotspots in the Himalaya account for a significant fraction of global sedimentary budget. They contribute ~8% of global riverine sediment flux (Hay, 1998) though they occupy only 0.07% of the total exoreic continental area (Table-3.10).

3.2.7 Control on Erosion

Synthesis of available data on erosion rates in the Himalaya show two trends with runoff (Fig-3.9). One is a group of four basins (Kosi, Ganga upstream of Patna, Mishmi Hills and Eastern Himalaya) having lower erosion rate and shallower slope with runoff and the other is a group of three basins (the Gandak and the eastern and western syntaxes) with much higher erosion rate and steeper slope with higher runoff. It has been shown for the Brahmaputra that physical erosion is controlled by a combination of climate and tectonics specifically by runoff and relief (Singh and France-Lanord, 2002; Singh, 2006). Among the three sub-basins of the Ganga system, the erosion rate of the Gandak is significantly higher than that of the Kosi and the Ganga basins upstream of Patna (Fig-3.9). This is an indication that in the Gandak basin there are additional factors which enhance its physical erosion, such as higher relief and focused precipitation. Available data (Bookhagen and Burbank, 2006) on elevation and relief for the Alaknanda, the Ghaghara, the Gandak and the Kosi show that among them relief is highest for the Gandak (Fig-3.10). The Gandak basin is also characterised by pockets of very high precipitation, particularly in the Higher Himalaya over its headwaters (Fig-2.4). The precipitation in these regions is much higher compared to that over the Ghaghra and the Kosi (Fig-2.4; Bookhagen and Burbank, 2006). Further, within the Gandak basin in the Higher Himalaya, the highest precipitation coincides with high relief on its southern slope. This combination of high precipitation (Fig-2.4) and high relief (Fig-3.10) seem to be driving the high erosion rates in the Gandak basin. It has been reported (Hodges et al., 2004; Thiede et al., 2004; Wobus et al., 2005) that in general, high precipitation over the southern slope of the HH promotes high erosion in the region. Over and above the general trend, there are regions of focused erosion in the Higher Himalayan sector of the Gandak basin, where intense precipitation (Fig-2.4) and high relief overlap. The headwaters of the Ganga around Rishikesh also receive intense precipitation over the Lesser Himalayan drainage (Fig-2.4). The relief of the Lesser Himalaya is low and hence intense precipitation does not lead to enhanced erosion rate. Thus the results for the Gandak, the Brahmaputra (Singh, 2006) and the Indus (Leland et al.,1998) basins indicate that intense precipitation over regions of high relief promotes high erosion rates.

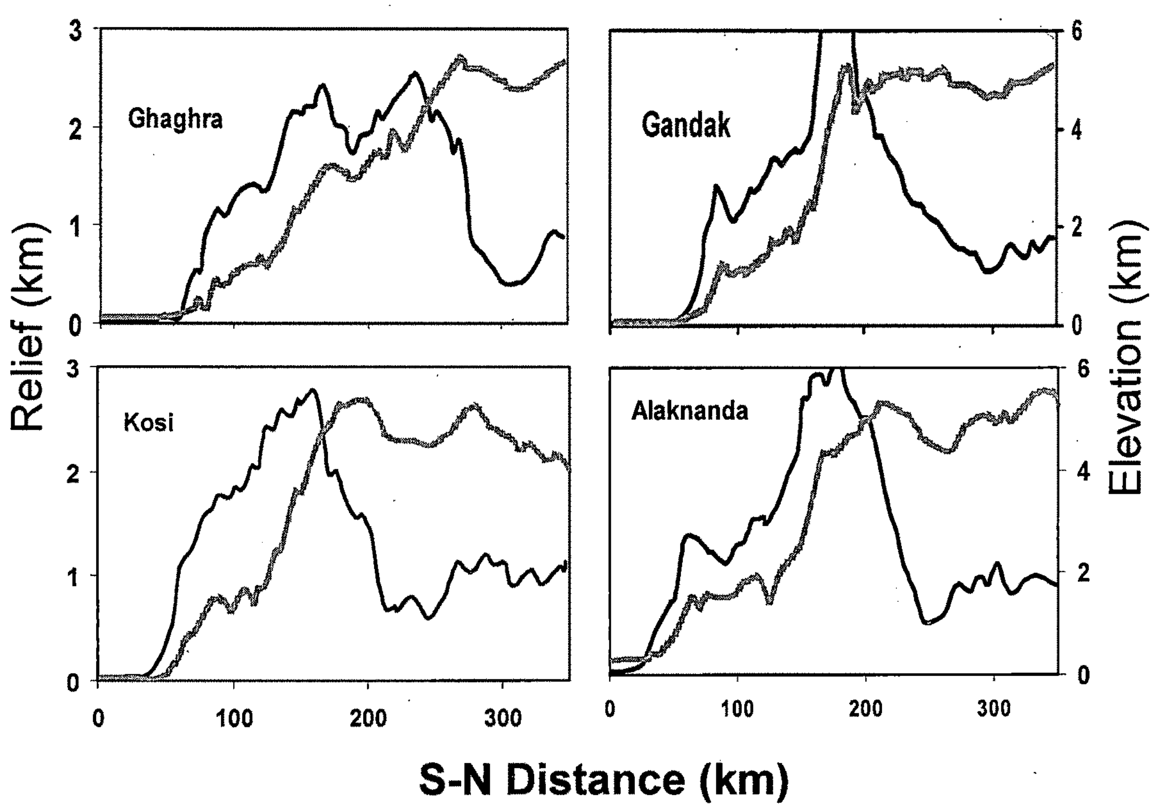

Fig-3.10: Elevation (grey line) and relief (black line) profiles of selected rivers of the Ganga basin (Bookhagen and Burbank, 2006). The relief of the Gandak drainage in the Higher Himalaya is higher than that of the others.

Relief of the Brahmaputra around the syntaxis is higher than 3.3 km (Finnegan et al., 2008) and comparable to that of the Gandak. The erosion rates in the syntaxes are ~10-14 mm yr^{-1} along the Brahmaputra (Burg et al., 1998; Singh, 2006) and 3-12 mm yr^{-1} along the Indus (Burbank et al., 1996; Garzanti et al., 2005; Leland et al.,1998), however, are higher than that of the Gandak basin, ~6 mm yr^{-1}. This study, thus, brings out the role of hotspots within the HH where the physical erosion rates are much higher than average due to cumulative effect of high relief and high precipitation.

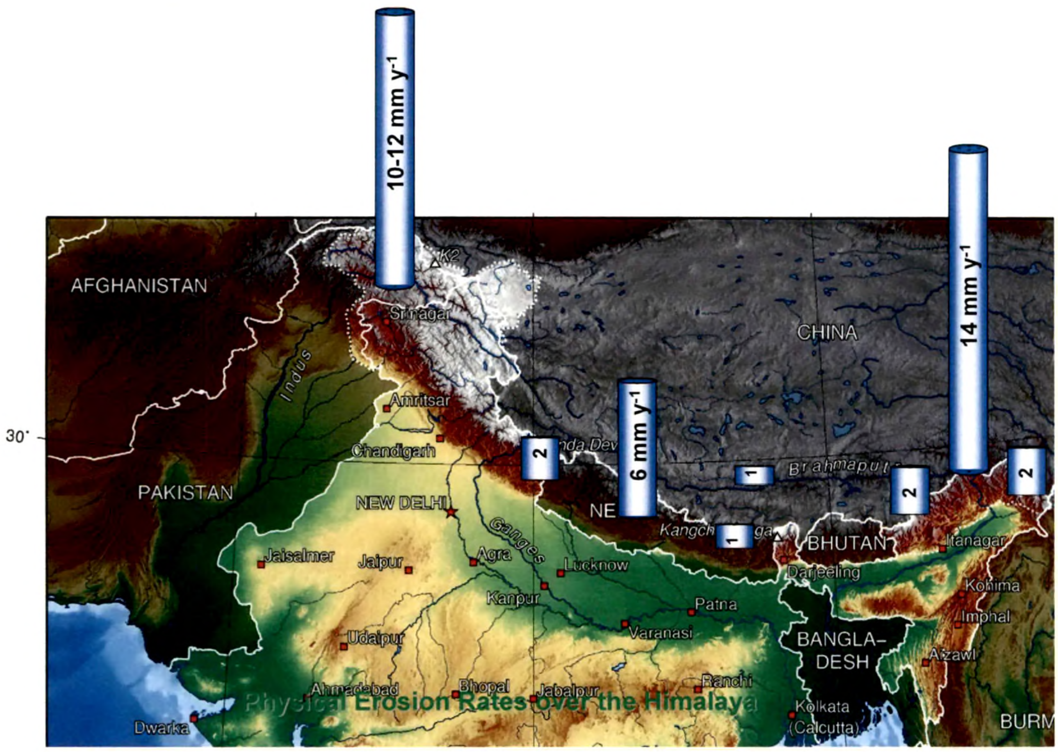

Fig-3.11: Locations of hotspots of physical erosion over the southern Himalaya. There are three hotspots, one each over the eastern and western syntaxes and third over the Gandak gorge. These hotspots control the sedimentary fluxes from the Himalaya and hence the sedimentary budget of the Bay of Bengal and the Arabian Sea.

3.2.8 Focused erosion and rapid uplift

This study along with those available in literature (Leland et al., 1998; Singh, 2006) highlights the presence of focused erosion along the 2500 km long WNW-ESE trending Himalayan Arc. It has been proposed (Wobus et al., 2003; Thiede et al., 2005) that intense and focused erosion followed by isostatic rebound cause rapid uplift of the Himalaya. High and focused erosion around the eastern syntaxis in the Brahmaputra, around the western syntaxis in the Indus and in the Gandak sub-basin are unloading large amount of sediment from the Himalaya (Fig-3.11). Due to this localized unloading, regions around them are uplifting more rapidly compared to other regions (Molnar and England, 1990; Montgomery, 1994; Zeitler et al., 2001). This in turn, can be responsible for high peaks of the Annapurna and Dhaulagiri in the Gandak basin similar to those of the Namche Barwa and Gyala Peri in eastern syntaxis and the Naga Parbat in western syntaxis basins (Zietler et al., 2001). The uplifting blocks may also be responsible for the micro-seismicity observed around MCT/MBT (Pandey et al., 1999; Kayal, 2001).

3.3 Summary

Sr and Nd isotope compositions of silicate fractions of the Ganga sediments in the plain have been used as proxies to trace sediment sources to the Ganga plain and to determine the spatial variability in physical erosion among the various sub-basins of the Ganga system. These studies reveal that more than two thirds of the sediments of the Ganga plain are derived from the Higher Himalaya and that the Gandak sub-basin contributes about half of the Ganga sediments at Rajmahal near to its outflow. The erosion rates in the Himalayan drainage of the different sub-basins of the Ganga, calculated based on the sediment proportions derived in this study and available sediment flux data, range from 0.5±0.25 to 6±3 mm yr^{-1}. The highest erosion rate is in the Himalayan drainage of the Gandak basin, ~6 mm yr^{-1} resulting from the combined effect of intense rainfall in its head waters and high relief. Results of this study along with those available in literature, suggest that, in general, the erosion rates in the HH are higher compared to other regions of the Himalaya, however even within the HH, there are hotspots where physical erosion is very rapid, 6 to 14 mm yr^{-1}. These regions are the gorges of the Brahmaputra, the Indus and the Gandak. These hotspots undergo mechanical erosion quite disproportionate to their aerial coverage and contribute ~8% of global riverine sediment flux to the oceans.