ISOTOPIC AND GEOCHEMICAL STUDIES OF ANCIENT AND MODERN SEDIMENTS

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By

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Dedicated to my parents

Certificate

I hereby declare that the work presented in this thesis is original and has not formed the basis for the award of any degree or diploma by any university or institution.

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Chapter 1

Introduction

1.1 Introduction

Erosive forces play a dominant role in shaping the surface of the Earth. Active mountainous regions are subject to persistent effects of weathering. Physical and chemical weathering of rocks on continents determines the exogenic cycles of elements and material transfer within and among surficial reservoirs. These erosive processes also play an important role in the biogeochemical cycles of elements by supplying nutrients and solutes to surface reservoirs such as soil, atmosphere, oceans and sediments. Rivers are a major agent of erosion. The signatures of the intensity and nature of weathering and erosion of rocks are contained in the abundance and composition of dissolved and particulate phases of rivers.

The Himalaya is a major geomorphic feature on the surface of the Earth. It stretches over ~2500 km in length, from the Nanga Parbat in the west to Namche Barwa in the east with high rise peaks ranging between 500-8000 m above the mean sea level. It is one of the rapidly eroding landforms contributing ~6-12% of global sediment discharge to the oceans (Milliman and Meade, 1983; Hay, 1998; Galy and France-Lanord, 2001). A number of river systems drain the Himalaya, among them the Ganga-Brahmaputra (G-B) system ranks first among the world rivers in sediment supply to the ocean and fourth in water discharge (Holman, 1968; Milliman and Meade, 1983; Berner and Berner, 1997; Hay, 1998). Together these two rivers discharge ~1x10^{12} m^3 of water annually to the Bay of Bengal (UNESCO 1971; Sarin et al 1989; Krishnaswami and Singh, 2005) containing ~100 million tons of dissolved solids (Sarin et al., 1989; Galy and France-Lanord, 1999; Singh et al., 2005) and ~1000-2300 million tons of particulate matter (Milliman and Meade, 1983; Hay, 1998; Ludwig and Probst, 1998; Galy and France-Lanord, 2001).

There have been a number of studies on the major ion chemistry of the Ganga-Brahmaputra rivers and on their solute and sediment fluxes (Meybeck,1979; Sarin and Krishnaswami, 1984; Sarin et al., 1989; Harris et al., 1998; Galy and France-Lanord, 1999; Islam et al., 1999; Galy and France-Lanord, 2001; Dalai et al., 2002; Bickle et al.,2003; Singh et al., 2005; Hren et al., 2007).

These studies led to better understanding of chemical and physical erosion rates of these basins, various factors influencing them and their impact on CO_2 drawdown from the atmosphere. A major goal of many of these investigations has been to test if young orogenic belts such as the Himalaya are undergoing rapid erosion of silicate rocks resulting in enhanced CO_2 drawdown and thus contributing to global cooling since the Cenozoic (Raymo and Ruddiman, 1992; Ruddiman, 1997; Huh, 2003). Further, these studies also have raised interesting issues pertaining to physical and chemical erosion of these basins, which continue to be topics of research among geochemists. For example, modeling and field based measurements have led to various suggestions on the relative roles of factors controlling erosion in different mountainous regions including the central Himalaya. Intensity and spatial distribution of physical erosion in the G-B drainage have been identified as key factors that determine sediment supply to the Bay of Bengal and play important role in regional tectonics of the Himalaya (Finlayson et al., 2002; Singh, 2006). Some of the important questions regarding physical erosion of the central Himalaya, particularly the Ganga basin, include (i) which are the dominant sources of sediments to the Ganga plains, e.g. Higher Himalaya and Lesser Himalaya, and/or peninsular India (ii) what is the variability in the rate of erosion among its sub basins (e.g. Ghaghra, Gandak, Kosi etc.) and what are its contributing factors? (iii) what is the interplay between physical erosion and regional tectonics?

Erosion rates of different regions of the Himalaya have been determined using various methods. These include thermo-chronology, (Burbank et al., 2003; Molnar 2003; Wobus et al., 2003, Hodges et al., 2004; Thiede et al., 2004) cosmogenic nuclides (Lal et al., 2004; Leland et al., 1998; Vance et al., 2003), mineralogical composition of particulate phases (Galy and France-Lanord, 2001; Garzanti et al., 2004, 2007) sedimentological properties (Sinha and Friend, 1994; Islam et al., 1999) and geochemical and isotopic measurements (Bouquillon et al., 1990; Clift et al., 2002; Singh and France-Lanord, 2002; Campbell et al., 2005; Foster et al., 2007; Singh et al., 2008). A key finding of some of these studies is the high and focused erosion in tectonically active regions, viz the

Western syntaxis, Nangaparbat (Leland et al., 1998) and the Eastern syntaxis, Namche Barwa (Burg et al., 1998; Singh and France-Lanord, 2002; Singh, 2006).

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 sediment budget in these basins is dominated by supply from the Higher Himalaya. Further, some of these studies also brought out large variability in physical erosion among the various sub-basins of the Brahmaputra with maximum in the Eastern Syntaxis (Singh, 2006). 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 role of various sub-basins in contributing to sediment budget is only poorly understood. A detailed and comprehensive study of the chemical and Sr and Nd isotopic composition of sediments from the Ganga mainstream and its major tributaries has been carried out as a part of this thesis 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 in its drainage, (ii) determine the fraction of sediments supplied from various sub-basins to the Ganga in the plain and (iii) estimate physical erosion rate over the western and the central Himalaya to assess their spatial variability, the various factors controlling it and its impact on regional geomorphology.

Physical erosion is considered as one of the drivers of chemical erosion (Bluth and Kump, 1994; Edmond et al., 1995; Louvat and Allegre, 1997; Gaillardet et al., 1997, 1999b; Anderson et al., 2002; Millot et al., 2002). Chemical weathering of silicate rocks exerts significant control on the CO_2 budget of the atmosphere and hence moderates the Earth’s climate (Walker at al., 1981, Raymo and Ruddiman, 1992; Edmond and Huh, 1997; France-Lanord and Derry, 1997; Ruddiman, 1997; Berner and Berner, 1997; Krishnaswami et al., 1999). The role of temporal variation in silicate weathering rates as a driver of climate change is a topic of debate among geochemists.

Orogenic uplift of mountains such as the Himalaya results in the development of high relief, steeper slopes and intense precipitation all of which promote enhanced erosion. Such enhanced erosion exposes primary minerals to chemical weathering. In this context, impact of the uplift of the Himalaya in contributing to enhanced silicate weathering and associated CO_2 drawdown has been a subject of investigation during the last couple of decades (Raymo, 1991; Raymo and Ruddiman, 1992; Molnar and England, 1992; Edmond and Huh, 1997; Galy and France-Lanord, 1999; Krishnaswami et al., 1999; Dalai et al., 2002; Jacobson et al., 2002; Huh, 2003; Bickle et al., 2005; Singh et al., 2005; Tipper et al., 2006; Hren et al., 2007). Contemporary silicate weathering rates in the Ganga-Brahmaputra-Indus (G-B-I) basins are higher compared to the global average as derived from major ion composition of river waters. These estimates rely on the knowledge of various end members that include atmospheric deposition, silicate/carbonate/evaporite weathering and groundwater input contributing to major ion abundances in rivers, their composition and the geochemical behaviour of elements in rivers (Krishnaswami et al., 1999). Both forward and inverse models have been used to estimate the silicate derived cations (Negrel et al., 1993; Krishnaswami et al., 1999; Galy and France-Lanord., 1999; Gaillardet et al., 1999b; Millot et al., 2003; Wu et al., 2005; Moon et al., 2007). In these models, particularly in the forward model, Na corrected for chloride is used as a proxy for silicate weathering.

These studies have yielded important data on the contribution of major ions to the Himalayan rivers from various sources and their impact on CO_2 drawdown from the atmosphere. In this context, one of the end members that can contribute Na to rivers is alkaline/saline salts of the Siwaliks, the Ganga plain and peninsular drainage. Reliable estimation of silicate erosion rates (and hence that of CO_2 consumption) in the Ganga basin therefore requires knowledge of the role of these soils in supplying Na to the Ganga. This forms a part of investigation of this thesis on chemical erosion in the Ganga plain and peninsular drainage and its role in contributing to major ion flux transported by the Ganga to the Bay of Bengal. Further, in this study attempt has been made to derive silicate erosion rates in the Ganga basin based on chemistry of both dissolved and particulate phases. This is based on the chemical composition of particulate matter transported by rivers and that of parent rocks (Martin and Meybeck, 1979, McLennan 1997, Stallard 1995; Roy et al., 1999; Canfield, 1997; Das and Krishnaswami, 2007). The advantage of particulate based approach is that it can directly yield silicate erosion rates, unlike that based on dissolved phase data which require apportionment of major ion contribution from silicate to the solute budget and estimate silicate weathering rates. Further, unlike the water data which yields contemporary erosion rates, the sediment data yields erosion rates averaged over the residence time of particles in the basin.

The potential of Sr isotope as a proxy for silicate weathering has prompted a number of studies on Sr isotopes in Himalayan rivers, particularly in the Ganga Brahmaputra system (Krishnaswami et al., 1992; Palmer and Edmond, 1992; Galy et al., 1999; Jacobson et al., 2002; Bickle et al., 2003). These studies have generated large volumes of high quality data which have wide implications on the Sr isotope budget of these rivers, their sources and their role in Sr isotope evolution of the ocean. The results show that G-B waters have moderate Sr concentration with highly radiogenic ^{87}Sr/^{86}Sr (Krishnaswami et al., 1992, 1999; Palmer and Edmond, 1992; Galy et al., 1999; Bickle et al., 2003; Dalai et al., 2003; Singh et al., 2006). The sources for radiogenic Sr in these waters are still debated. Chemical weathering of highly radiogenic silicates of the basin (Edmond, 1992; Krishnaswami et. al., 1992; Singh et al., 1998; Bickle et al., 2003), metamorphosed carbonates and vein calcites (Quade et al., 1997, 2003; Blum et al., 1998; Jacobson and Blum, 2000) have been suggested as potential sources. One of the issues pertaining to Sr isotope geochemistry of the Ganga waters is that Sr budget and isotopic composition is difficult to be explained in terms of supply only from silicates and carbonates (Krishnaswami and Singh, 1998; Krishnaswami et al., 1999; Dalai et al., 2003). This has led to propose that there are additional sources for Sr with low ^{87}Sr/^{86}Sr to balance its budget and/or that the contribution of Sr from carbonates estimated based on Ca abundance in water can be lower limit due to non-conservative behaviour of dissolved Ca, which results in its precipitation from water as calcite (Jacobson et al., 2002; Dalai et al., 2003). To probe into these issues in some detail and to better constrain Ca and Sr budgets in the Ganga, studies on chemical and Sr isotopic composition of waters, particulates and precipitated carbonates from the Ganga and its tributaries, have been carried out.

Enhanced drawdown of CO_2 due to silicate weathering in active mountains such as the Himalaya has been suggested as a potential cause of global cooling during the Cenozoic (Raymo and Ruddiman, 1992; Ruddiman, 1997). An alternative hypothesis is that of enhanced carbon burial in coastal and shelf sediments (Raymo, 1994; France-Lanord and Derry, 1997, Galy et al., 2007a). Photosynthetic production of organic matter is one of the principal mechanisms of atmospheric CO_2 consumption. A fraction of this organic matter is buried in sedimentary basins and can remain stored for extended periods of time under suitable conditions. This makes the sequestration of atmospheric CO_2 via burial of particulate organic carbon an important sink for atmospheric CO_2. However, the relative roles of carbon burial vs silicate weathering in determining atmospheric CO_2 budget is still a topic of investigation (France-Lanord and Derry, 1997; Galy et al., 2007a). In this study particulate organic carbon flux of the Ganga has been measured to determine its flux to the Bay of Bengal and compare with CO_2 consumption by silicate weathering.

1.2 Objectives of the thesis

1. To trace the sources of sediments to the Ganga basin in the plain and to determine the relative contributions of various sub-basins to the sediment budget based on Sr, Nd isotopes and sediment composition.
2. To determine the spatial variability in physical erosion rates among the sub-basins of the Ganga drainage and its implications to sediment provenance and regional tectonics.

3. To determine contemporary chemical erosion in the Ganga plain and peninsular sub-basins and their role in contributing to major ion budget of the Ganga at its out flow and the overall chemical erosion of the Ganga basin.
4. To determine major element and Sr abundances of bank sediments, their fine fraction and suspended matter from the Ganga river and apply them to derive silicate erosion rates.
5. To determine the abundance of dissolved major elements, Sr and $^{87}Sr/^{86}Sr$ in the Ganga and its tributaries and use these results in conjunction with sediment data to evaluate contemporary chemical and silicate erosion rates and budgets of Ca and Sr in the basin.
6. To determine the fluxes of particulate carbon transported by the Ganga to the Bay of Bengal based on inorganic and organic carbon contents of bed and suspended sediments and to compare it with CO_2 consumption via silicate weathering.

1.3 Structure of thesis

This thesis is divided into six chapters. The content of these six chapters are as follows.

Chapter-1 outlines the thesis topics addressed in this study. This chapter presents the current state of knowledge on these topics through a brief description of earlier studies in the Himalayan river basins, particularly the Ganga.

Chapter-2 describes the sampling details and analytical methods used for the measurements of various parameters. First part of this chapter discusses the general geology and the hydrogeology of the catchment whereas the latter part gives a brief description of sampling of river sediment and water samples and the various analytical methods used for their chemical and isotope analyses.

Chapter-3 is on the determination of physical erosion rates and its spatial distribution in the central Himalaya carried out in this work using Sr and Nd isotopes. The data has been used to derive information on the present day sources of sediments, erosion rates and its variability among the different sub-basins of the Ganga system. The implications of the results to regional tectonics and global riverine sediment budget are also presented.

Chapter-4 presents major ion data in the Ganga river along its entire stretch, and its tributaries and their temporal variations at selected locations. The chapter also presents results of Sr isotopes in water and Ca/Sr studies in seepage, drip and spring waters and in precipitated carbonates. These measurements have been used to determine chemical erosion rates in the Ganga sub basins (the Ganga plain and the peninsular drainage in particular), dissolved Ca and Sr budgets and to understand the factors contributing to temporal variations in major ion chemistry in dissolved phase.

Chapter-5 presents results of chemical composition of particulate phase of the Ganga and their application to learn about silicate erosion and particulate carbon fluxes to the Bay of Bengal and their implications.

Chapter-6 summarises the results of this thesis and briefly outlines future perspectives.

Chapter 2

Materials and Methods

The primary goals of this thesis, as detailed in the Introduction, are to determine (i) the sources of sediments to the Ganga basin in the plain in terms of various sub-basins (ii) spatial variability in physical and chemical erosion among the Ganga sub-basins (iii) chemical and silicate erosion in the Ganga drainage based on elemental composition of water and sediments and (iv) the budget of Sr and ^{87}Sr/^{86}Sr in the Ganga and its relation to the geochemistry of dissolved Ca. Addressing these goals require sampling of water, sediment and other relevant samples from the Ganga basin and knowledge of basin lithology and hydrology. This chapter provides a description of these details, viz lithology of the basin, the sampling locations, their collection and analytical methods. The accuracy and precision of various measurements are also given in this chapter.

2.1 Study Area

This work, as mentioned in the Introduction chapter, is focused on studies of dissolved and particulate components of the Ganga river system. The Ganga River, known as the Bhagirathi in the Himalaya, originates from the Gangotri glacier at "Gaumukh" in the Higher Himalaya. At Devprayag, the Alaknanda joins the Bhagirathi and forms the Ganga (Fig-2.1a). The head waters of the Alaknanda, the Saraswati and the Dhauli, emerge from the Bhagirathi Kharak (east of the Gangotri glacier) and the Bamak glaciers. At Haridwar, the Ganga descends to the plains after cutting across the Siwalik ranges. The Ganga receives many tributaries, the Ramganga, the Gomti, the Ghaghra, the Gandak and the Kosi from the north and the Yamuna and the Son from the south (Fig-2.1b). The Gomti and the Son are two major tributaries of the Ganga which have non-Himalayan sources.

The Gomti is a rain fed river with its entire drainage in the Ganga plain. It originates from the reservoir Madho-Tanda (Fig-2.1b; Miankot, elevation ~200 m, 28º 34´ N and 80º 07´ E) in the Pilibhit district, Uttar Pradesh located ~ 50 km south of the foot hills of the Himalaya. It drains the interfluve sediments between the Ganga and the Ghaghra, through an area of ~30×10^3 km^2, prior to joining the Ganga at Udyar Ghat near Ghazipur, ~30 km downstream of Varanasi (Fig-2.1b). The annual water discharge of the Gomti is 7.4 km^3, with most of its flow during the southwest monsoon. The river drainage of the Gomti has a gentle slope, in the range of 550 and 100 mm km^{-1} with a maximum relief of ~25 m (Singh et al., 2005a; Singh et al., 2005b).

The Yamuna is the largest tributary of the Ganga in terms of drainage area ~366 x10^3 km^2 and accounts for ~40 % of the Ganga basin. It originates from the Yamunotri glacier in the Himalaya and descends to the Ganga plain at Dak Pathar, after merging with a number of tributaries in the Himalaya (Dalai et al., 2002). The annual water discharge of the Yamuna at Tajewala (Fig-2.1b), near the foot hills of the Himalaya is 10.8 km^3 yr^{-1}, about 12% of its discharge at Allahabad, 93 km^3 yr^{-1} (Rao, 1975). Nearly 75% of the discharge of the Yamuna occurs during June-Sept, the south west monsoon period. The Chambal, Sind, Betwa and the Ken are the major tributaries of the Yamuna, all of which originate in and flow almost entirely through peninsular India. All these tributaries join the Yamuna in the Gangetic plain before its confluence with the Ganga at Allahabad (Fig-2.1b). Of the total drainage area of the Yamuna, ~3% is in the Himalaya, 63% in the peninsular basin and 34% in the Ganga plain. In estimating this, the sum of the areas of the Chambal, Sind, Betwa and the Ken are taken to be equal the peninsular drainage. The headwater basins of the Yamuna tributaries in the peninsular drainage have a slope of ~750 mm km^{-1}. Drainage basins of both the Gomti and the Yamuna, particularly in the plain, are endoreic with micro-depressions or level topography with poor drainage. Rain and flood waters often get trapped in these basins eventually subject to drying during summer. This results in the deposition of various salts, such as sodium carbonate, sodium bicarbonate, sodium chloride and sodium sulphate in the basin (Agarwal and Gupta, 1968; Bhargava et al., 1981; Pal et al., 2003). Some of these salts make their way to rivers and also to groundwater during subsequent wetting cycles in monsoon. The salinization of soils has been further aggravated with the development of canal systems in the Gangetic plain for irrigation.

The Son is another tributary of the Ganga with its drainage predominantly in peninsular India. A part of its basin prior to its confluence with the Ganga is in the Ganga plain. The Son originates from the Amarkantak in the Bundelkhand plateau and merges with the Ganga ~25 km upstream Patna (Fig-2.1b). The Son is also a rainfed river with annual discharge of ~32×10^9 m^3 and drainage area of ~71×10^3 km^2 with ~10×10^3 km^2 in the plain (estimated using global mapper). The headwaters of the Son are in the mountainous region of the Indian craton and Vindhyan having a slope of ~1500 mm km^{-1}, its outflow in the Gangetic plain, however, has a much gentler slope, ~100 mm km^{-1}. The Son is also a seasonal river with most of its discharge during monsoon. Its drainage receives an annual rainfall of ~1300 mm yr^{-1} (http://www.tropmet.res.in). Its runoff is ~450 mm yr^{-1}.

The Kosi (Sapta Kosi), Gandak (Narayani) and the Ghaghra (Karnali) are major rivers of the Ganga system, all of them originating from glaciers and snow-fed lakes of the Nepal Himalaya. The Kosi river system consists of the Arun, the Sunkosi and the Tamakosi rivers (Fig-2.1a). Flowing through a narrow gorge and called the Kosi after it enters into the Indian territory. The Kosi has the second largest drainage area (~75×10^3 km^2; Table-2.1) among the tributaries of the Ganga after the Yamuna. It is joined by the tributaries, the Bagmati and the Kamala before it merges in to the Ganga. The Gandaki river system in central Nepal consists of the Kaligandaki, Budhigandaki, Marsyandi, Trishuli and Seti rivers. The Kaligandaki and the Trishuli are the main tributaries of this system. The Kaligandaki converges with the Trishuli and is called the Narayani which goes on to meet the Ganges as the Gandak near Hazipur. The Ghaghra river system originates from the western Nepal. It consists of the Kali, Karnali, Seti and the Bheri rivers and has the highest water discharge (~95×10^9 $m^{3)}$ among the tributaries of the Ganga system (Table-2.1). The Ghaghra merges with the Ganga near Revilganj. Among these three basins, the precipitation over the Gandak drainage in the Higher Himalaya is much higher compared to those over the Ghaghra and the Kosi headwaters. It also has the highest relief of >3 km as compared to that of the Ghaghra (2.6 km) and the Kosi (2.8 km) among the Himalayan tributaries of the Ganga (Bookhagen and Burbank, 2006).

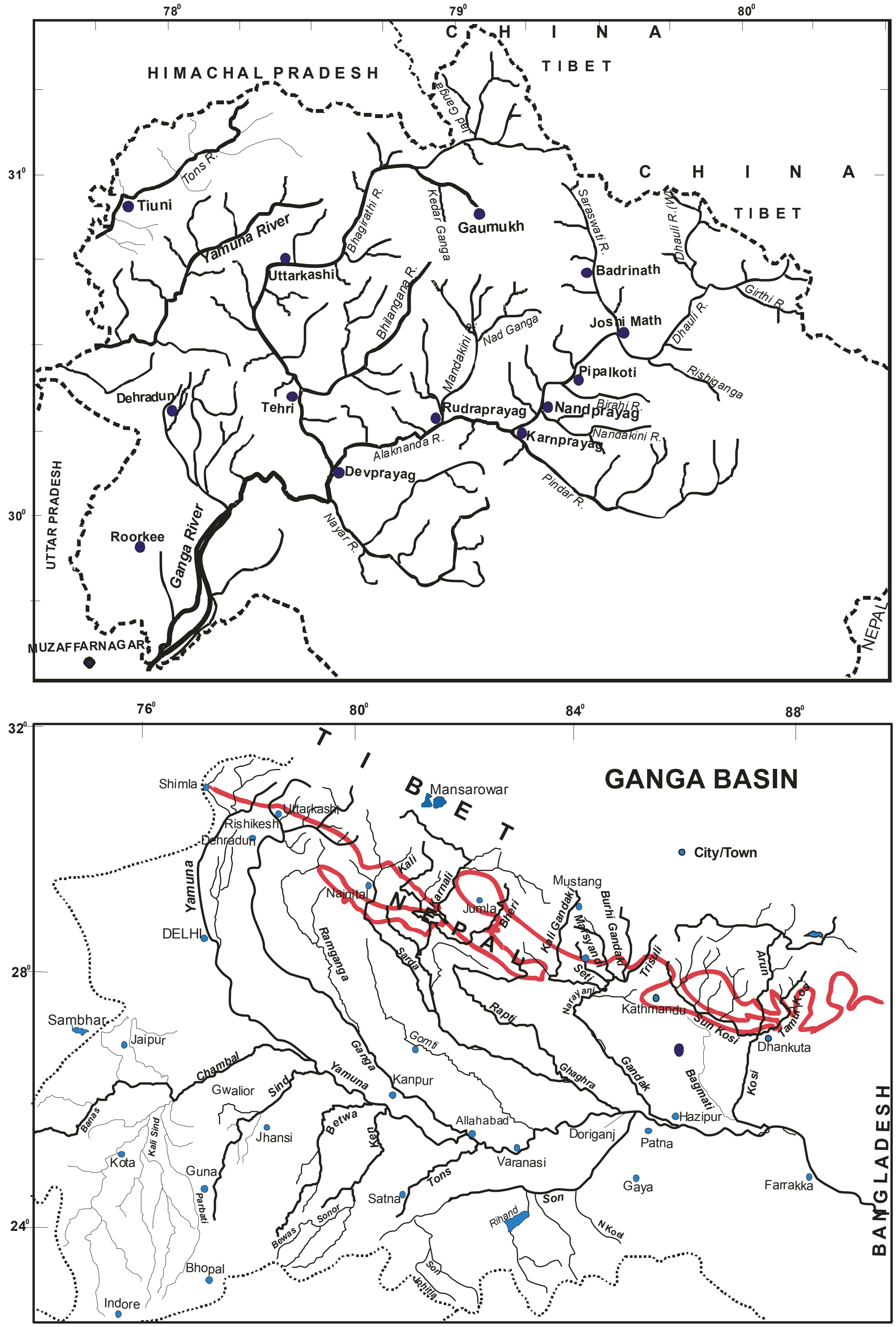


Fig-2.1a & 1b: Map of the Ganga basin. (a): the head water basin of the Ganga in the Himalaya (b): the Ganga basin, with its major tributaries in the Himalaya and the plains. The red line is MCT.

The Gandak and the Kosi rivers have an average gradient of 5 km in 200 km whereas the Ghaghra has a marginally lower gradient of 5 km in 300 km (S-N distance) across the Himalaya. Table-2.1 gives the discharge and drainage area of the Ganga and some of its tributaries at locations prior to their confluence with the Ganga in the plains. The total drainage area of the Ganga basin is ~935×10^3 km^2 with a discharge 380×10^9 m^3 yr^{-1} at Farakka, near the Indo-Bangladesh border (Table-2.1).

Table 2.1: Drainage Area and Discharge of major rivers of the Ganga System

River	Location	Area		Discharge	
		Total	Himalaya	Total	Himalaya
		10^3 km^2		10^9 m^3 yr^{-1}	
Bhagirathi	Devprayag	7.8	7.8	8.3	8.3
Alaknanda	Devprayag	11.8	11.8	14.1	14.1
Ganga	Rishikesh	21.7	21.7	23.9	23.9
Ramganga*		32.5	2.5	15.6	9.8
Yamuna	Allahabad	366	9.8	93.0	10.8
Tons*		16.9	nil	5.9	nil
Gomti*	Sighauna	30.5	nil	7.4	nil
Ghaghra*	Revilganj	128	57.6	94.4	63.4
Gandak	Hazipur	46.3	31.8	52.2	49.4
Kosi*	Dumariaghat	74.5	51.4	62.0	48.2
Son*	Koilawar	71.3	nil	31.8	nil
Ganga	Farakka	935	176	380	206

Data from[*Galy*, 1999; *http://www.grdc.sr.unh.edu*, 2004; *Rao*, 1975]
*Before confluence with the Ganga mainstream

The rainfall and runoff among the different regions of the Ganga basin show significant heterogeneity with the highest runoff in excess of a meter yr^{-1} in the Himalayan drainage (Donold,1992) and the lowest of ~0.3 m yr^{-1} over the Gangetic Plains and the peninsular regions (Rao,1975). The southwest monsoon (June-September) is the major source of water to the Ganga system; however snowmelt and groundwater also contribute water to the rivers draining the Himalaya (Bahadur, 1997). Melt water from the Himalayan glaciers contribute

~15% of the Ganga river discharge at Haridwar (Das Gupta, 1975). The Ganga divides into two distributaries before it enters the Bangladesh. It joins the Brahmaputra in Bangladesh and discharges into the Bay of Bengal through many distributaries.

2.2 Geological setting

The Ganga catchment is spread over the Himalaya in the north, peninsular India in the south and the Gangetic plain between them. The head waters of the Ganga, its tributaries the Ghaghra, Gandak and the Kosi have a significant part of their drainage in the Himalaya. The tributaries of the Yamuna (the Chambal, Sind, Betwa and the Ken; Fig-2.1b) and the Son flow mainly through peninsular India. The rivers Gomti and the Ganga down stream of Haridwar drain the Ganga plain.

The Himalaya in the Ganga basin is made of four major lithological units, the Tethyan Sedimentary Series (TSS), the Higher Himalaya (HH), the Lesser Himalaya (LH) and the Siwalik (Gansser, 1964; Valdiya, 1980; Sarin et al., 1989; Bickle et al., 2001). The lithology of each of these units over the entire Himalayan range, from east to west, is roughly the same (Gansser, 1964; Le Fort, 1975; Valdiya, 1980). The head waters of the Alaknanda, Ghaghra, Gandak and the Kosi lie in the Tethyan Sedimentary Series (TSS). The TSS is composed of carbonates and clastic sedimentary rocks (Oliver et al., 2003). The HH consists of ortho- and paragneisses, migmatites and metamorphosed carbonates and calc-silicates. Granites, gneisses and leuco-granites which form the Higher Himalayan Crystallines (HHC) are exposed widely in this region. South of the HH, and separated by the Main Central Thrust (MCT) is the Lesser Himalaya (LH). The lithologies of the LH are meta-sedimentary rocks which include limestones, dolomitic carbonates, shales, slates, quartzites, evaporites and calc-silicates. The LH is divided into two sedimentary sequences, the outer and inner belts, separated by the Lesser Himalayan Crystallines (LHC) consisting of granites and gneisses (Valdiya, 1980). The Siwaliks is the southernmost unit of the Himalaya formed by the uplift of sediments deposited in its foreland basin during the Mio-Pliocene (Valdiya, 1980). It consists mostly of sandstones.

The Peninsular drainage: The major lithologies exposed in this drainage are the Bundelkhand crystallines (granites), the Vindhyan sediments (carbonates, shales and sandstones) and the Deccan basalts (Krishnan, 1982; Singh et al., 2008). Besides these lithologies, saline and alkaline soils are dispersed to varying degrees in the recent alluvium of this basin including the Chambal drainage around Gwalior (Agarwal and Gupta, 1968; Bhargava and Bhattacharjee, 1982; Sarin et al., 1989; Tamgadge et al., 1996; Rengarajan et al., 2008). The tributaries of the Yamuna (Chambal, Sind, Betwa and Ken) and the Son though drain peninsular India, they flow through different lithologies. The Yamuna tributaries (Chambal, Sind, Betwa) drain the Deccan Traps and the Vindhyans whereas the Son lies mainly in the Vindhyan-Bundelkhand plateau. The latter region is made of crystalline igneous and metamorphic rocks of the Archean shield and limestones, shales and sandstones of the Vindhyans (Krishnan, 1982). Southern tributaries of the Son drain the sedimentary sequences of the Gondwana comprising of sandstone, shales and carbonates (Krishnan, 1982).

The Ganga plain: is a major alluvial tract that has evolved through time (Singh, 1996). It is formed by the accumulation of detritus from the source regions of the Ganga and its tributaries, the Higher and the Lesser Himalaya (Singh, 1996; Singh et al., 2008; Rai et al, 2008) and consists of beds of clay, sand and gravel (Sinha et al., 2005). These alluvial sediments also contain impure calcareous matter in the form of irregular concretions in clays or as independent layers, locally known as “kankar” (Agarwal et al., 1992; Singh et al., 2004, Sinha et al., 2006). These kankars are formed from river water/groundwater during their drying cycles and are dispersed in sediments of the plain (Agarwal et al., 1992; Srivastava, 2001; Sinha et al., 2006). Besides these kankar carbonates, detrital carbonate brought from the Himalaya is also present in these alluvial sediments. The carbonates are predominantly calcium carbonate, though magnesium carbonate is also reported in some of them (Agarwal et al., 1992; Singh et al., 2004; Sinha et al., 2006). The abundance of calcareous matter in the plain varies significantly, with values as high as 30% (Wadia, 1981; Gupta and Subramanian, 1994). At places these carbonates form large deposits which are mined locally (Kumar, 2005). A significant part of the soils in the Gomti and the Yamuna drainage in the Ganga plain is impregnated with alkaline and saline salts formed locally due to the endoreic nature of the basins and excessive use of river and groundwater for irrigation (Agarwal and Gupta, 1968; Bhargava and Bhattacharjee, 1982; Tamgade et al., 1996; Pal et al., 2003). The abundance of these soils varies significantly within and among the basins. For example, in the Ganga plain high content is reported (Singh et al., 2004) in the stretch between Kanpur to Ghazipur (Ganga), Delhi to Allahabad (Yamuna) and Madho-Tanda to Ghazipur (Gomti). In general, the abundance of these alkaline/saline soils is more towards the western basin of the Ganga due to the semi-arid climate and basin characteristics. The soils, as mentioned earlier, contain many sodium salts (Agarwal and Gupta, 1968; Bhargava et al., 1981; Bhargava and Bhattacharjee, 1982; Datta et al., 2002, Singh et al., 2004).

2.3 Climatic features of the Ganga Basin:

The Ganga catchment and its sub-basins, covering the northern India and Nepal (Fig-2.1a & 2.1b) experience tropical monsoon climate with varying intensities (Devi, 1992) induced by the altitude and mountain barriers. The temperature in the Ganga catchment reaches its minimum in January and the maximum in the month of June. The temperature decreases with the onset of southwest monsoon in June. In the Ganga basin, the cold period extends from December to February with the coldest in January when air temperature dips below 10°C. The air temperatures starts rising from March onwards and persists up to mid June with May being the hottest month in the basin (Assessment and development study of river basin Series ABSORBS/7/1982-83). In the Ganga plain, at many locations, the daily mean temperature exceeds to 40°C in May causing extensive evaporation. The maximum evaporation takes place during March to July in the entire basin (Fig-2.2). The southwest monsoon sets in the

Ganga basin during June-July and continues for about 3-4 months. This is the major source of water for the Ganga basin and is reflected in its monthly water discharge pattern (Fig-2.3) for the four locations (Rishikesh, Allahabad, Patna and Azamabad). The spatial and temporal variation in water discharge of the Ganga river are regulated by its tributaries which in turn are controlled by rain fall in their basin.

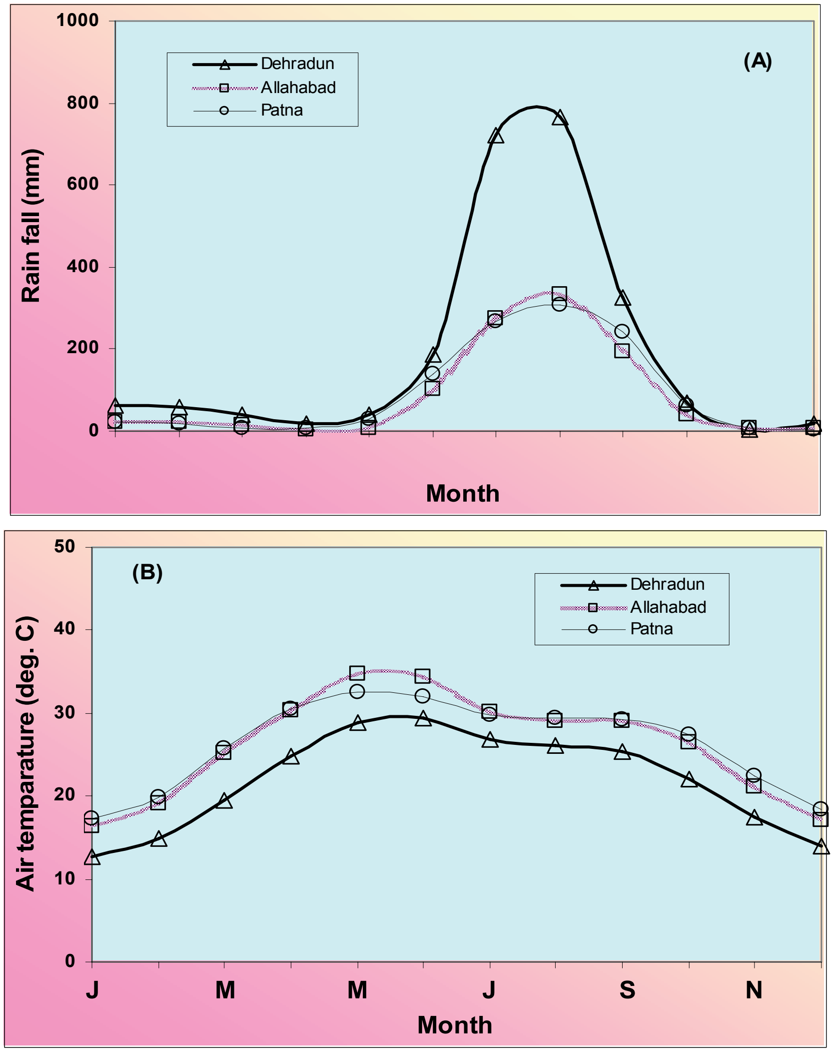


Fig-2.2: Monthly variation of (A) Rainfall; the maximum rainfall is restricted to Jun-Sept, southwest monsoon. (B) Mean air temperature at the different location in the Ganga basin. (Data Source: Assessment and development study of river basin Series ABSORBS/7/1982-83)

The geographical distribution of rain fall (Fig-2.4; averaged over 10 years) clearly shows a negative gradient form east to west in the plains. Rainfall contours over the Ganga drainage for Jan 1998 -May 2007 (Fig-2.4) (http://disc2.nascom.nasa.gov/Giovanni/tovas/TRMM_V6.3B43.shtml) show that belts of higher rainfall are observed close to and paralleling the Main Central Thrust (MCT) particularly over the Gandak sub-basin and in the Son and Ken headwaters in peninsular India and lower rainfall in the plains and over catchments of the southern tributaries. High precipitation is also observed over the Lesser Himalayan catchment of the Ganga sub-basin around Rishikesh. This variability in precipitation among different regions of the Himalaya and the plain, results in significant regional differences in runoff and in contribution to the water budget of the Ganga. Thus the Himalayan basin of the Ganga has a runoff of about 1m yr^{-1} and accounts for ~54% of its water discharge, in comparison the peninsular rivers contribute ~22% of water discharge with a runoff of ~0.3 m yr^{-1} (Galy, 1999; Rao, 1975).

Annual rainfall in the Gomti basin, based on data for the decade (1997-2006), average ~1025 mm (http://www.tropmet.res.in/; http://disc2.nascom.nasa.gov/Giovanni/tovas/TRMM_V6.3B43.shtml;Fig-2.4) whereas its runoff is only 240 mm yr^{-1}. Thus, about 75 % of rainfall in the Gomti drainage is either returned to the atmosphere through evaporation/evapotranspiration and/or stored as groundwater. Rainfall in the drainage basin of the Yamuna shows significant spatial variation (Fig-2.4). Its headwaters in the Himalaya receive ~1300 mm yr^{-1} rainfall which decreases to ~700 mm yr^{-1} around Delhi in the Ganga plain. The peninsular drainage of the Yamuna receives an annual rainfall of ~800 mm (http://www.tropmet.res.in, TRMM). The runoff of the Yamuna in the Himalayan region is ~1100 mm yr^{-1} whereas in the peninsular drainage it is much lower, ~250 mm yr^{-1}.

2.4 Sampling

For this work, samples of water, sediments and particulate matter from the entire stretch of the Ganga in India, from Gangotri near its source to Rajmahal near its outflow and from the major tributaries of the Ganga in the Himalaya and the plains were collected. The sampling work was done during three field campaigns, May 2003, May 2004 and October 2006.

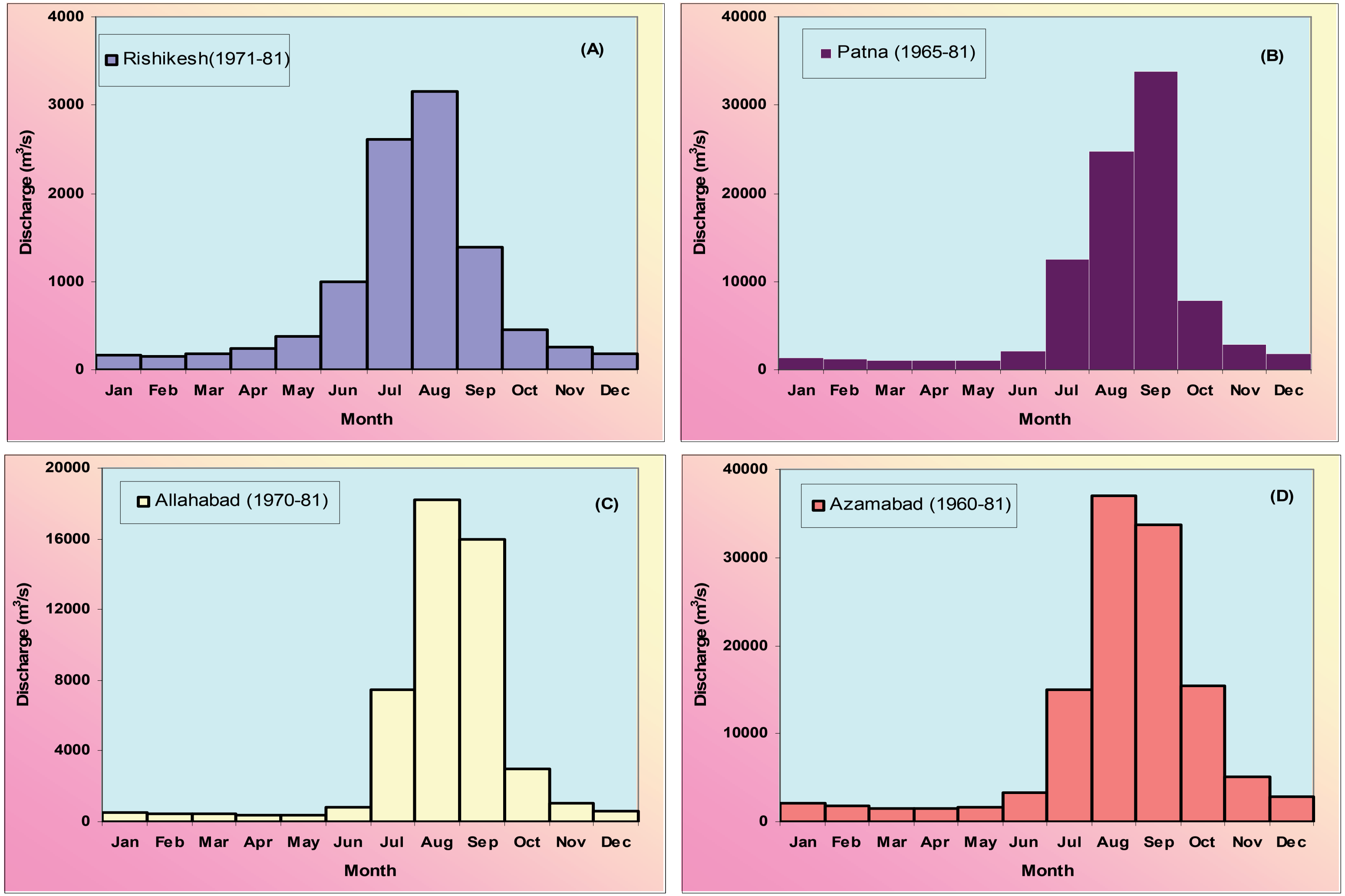


Fig-2.3 (A, B, C & D): Monthly variation of water discharge of the Ganga river at different locations along its course. (Data Source: Assessment and development study of river basin Series ABSORBS/7/1982-83)

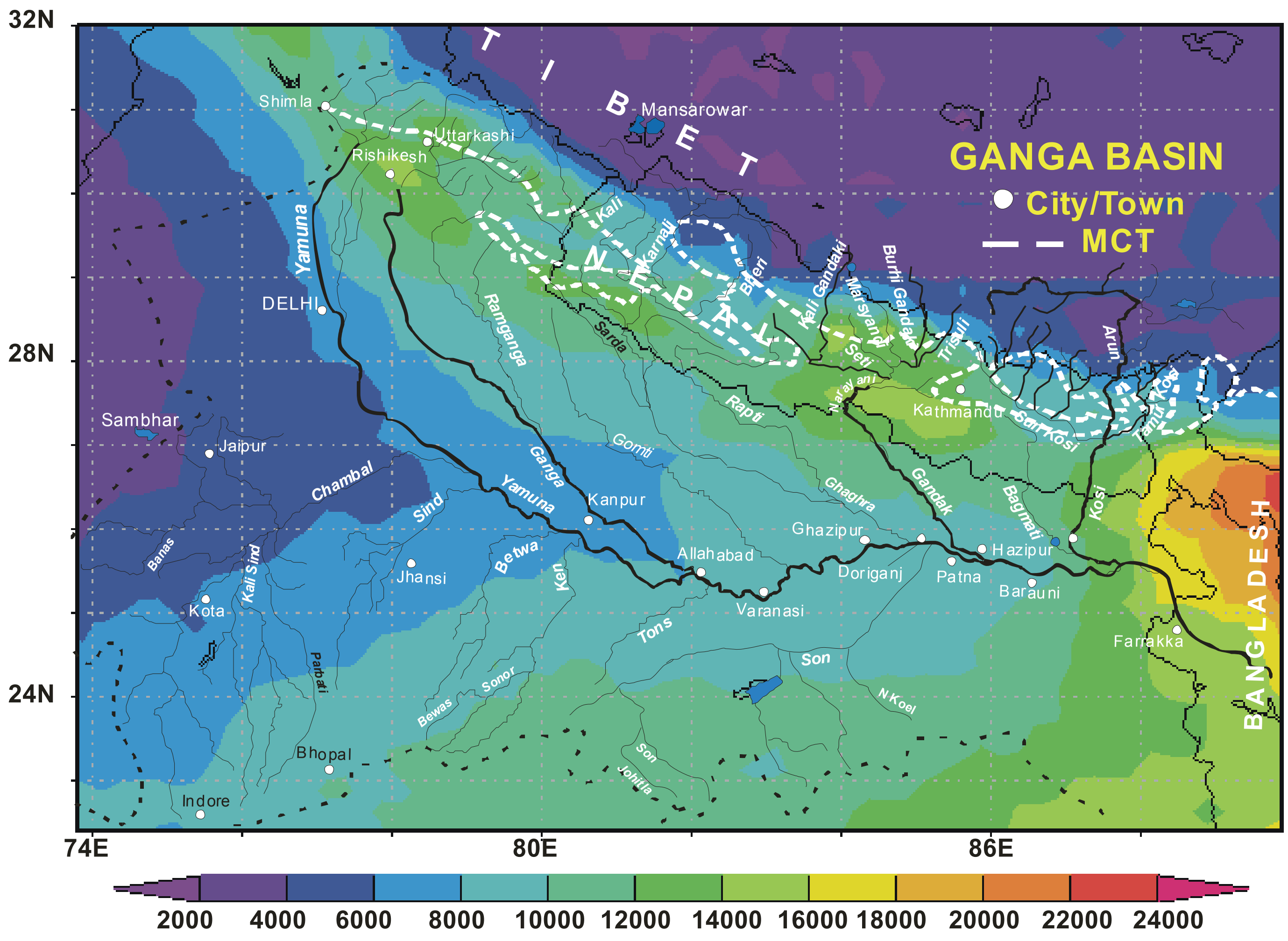


Fig-2.4: Precipitation over the Ganga drainage for the period January 1998 to May 2007, from TRMM (expressed in mm). The precipitation over the Gandak drainage in the Higher Himalaya is much higher compared to those over the Ghaghra and the Kosi head waters. The region of higher rainfall in the Gandak drainage coincides with the high relief. The Main Central Thrust (MCT) is marked as dashed line.

Table - 2.2: Sample locations of river sediments

Sample code	River	Date d/m/y	Location	Latitude N	Longitude E	Altitude m	Drainage Lithology
Ganga Mainstream							
RS03-3	Bhagirathi	02.05. 03	Gangotri	30° 60'	78° 56'	2968	HH
RS03-7	Bhagirathi	03.05. 03	Uttarkashi	30° 44'	78° 27'	1192	HH
RS03-1	Ganga	01.05. 03	Rishikesh	30° 31'	78° 21'	335	LH, LH
BR05-1	Ganga	25.05.05	Kanpur				GP,SW, LH, HH
BR352, 351**	Ganga	14.05. 04	Allahabad	25° 26'	81° 53'		GP,SW, LH, HH, P
BR06-12-2	Ganga	20.10.06	Allahabad	25° 30’	81° 52’		GP,SW, LH, HH, P
BR382, 383**	Ganga	17.05. 04	Varanasi	25° 18'	84° 00'		GP,SW, LH, HH, P
BR06-14-2	Ganga	21.10.06	Varanasi	25° 18’	83° 01’		GP,SW, LH, HH, P
BR06-10-1	Ganga	19.10.06	Ghazipur	25° 32’	83° 12’		GP,SW, LH, HH, P
BR06-802	Ganga	19.10.06	Doriganj	25° 44’	84° 49’		GP,SW, LH, HH, P
BR306	Ganga	07.05. 04	Patna	25° 37'	85°09'		GP,SW, LH, HH, P
BR06-303	Ganga	16.10.06	Patna	25° 37’	85° 09’		GP,SW, LH, HH, P
BR315, 314**	Ganga	08.05. 04	Barauni	25° 23'	86° 00'		GP,SW, LH, HH, P
BR06-404	Ganga	17.10.06	Barauni	25° 22’	86° 00’		GP,SW, LH, HH, P
BR324, 325**	Ganga	09.05. 04	Rajmahal	25° 04'	87° 50'		GP,SW, LH, HH, P
BR06-101	Ganga	15.10.06	Rajmahal	25° 03’	87° 50’		GP,SW, LH, HH, P
Alaknanda							
RS03-28	Alaknanda	05.05.03	Birhai, Bef. Confl[a]	30° 25'	79° 23'	1037	LH, HH
RS03-27	Birahi Ganga	05.05. 03	Birahi			1039	LH, HH
RS03-31	Pindar	05.05. 03	Pindar Valley	30° 05'	79° 28'	1034	LH, HH
Bhagirathi Tributaries							
RS03-9	Syansu Gad	03.05. 03		30° 29'	78° 24'	838	LH, HH
RS03-12	Bhilangna	03.05. 03	Ghanshyali				LH, HH
Tributaries in Plain							
BR348	Yamuna	15.05. 04	Allahabad	25° 25'	81° 50'		GP,SW, LH, HH, P
BR06-13-2	Yamuna	20.10.06	Allahabad	25° 25’	81° 50’		GP,SW, LH, HH, P

BR365, 364**	Rapti	15.05. 04	Gorakhpur	26° 44'	82° 21'	GP,SW, LH, HH
BR378	Gomti	16.05. 04	Before Confl.	25° 30'	83° 08'	GP
BR06-11-3	Gomti	19.10.06	Ghazipur	25° 30’	83° 08’	GP
BR355, 356**	Ghaghra	15.05. 04	Ayodhya	26° 49'	82° 12'	GP,SW, LH, HH
BR371, 372**	Ghaghra	15.05. 04	Doharighat			GP,SW, LH, HH
BR343, 344**	Ghaghra	12.05. 04	Revelganj	25° 49'	84° 35'	GP,SW, LH, HH
BR06-905	Ghaghra	19.10.06	Revilganj	25° 49’	84° 36’	GP,SW, LH, HH
BR06-205	Son	16.10.06	Koilawar	25° 34’	84° 48’	P
BR336**, 335**	Gandak	11.05. 04	Barauli	26° 22'	84° 45'	GP,SW, LH, HH
BR310	Gandak	07.05. 04	Hazipur	25° 41'	85° 11'	GP,SW, LH, HH
BR06-701	Gandak	18.10.06	Hazipur	25° 41’	85° 11’	GP,SW, LH, HH
BR330, 331**	Kosi	10.05. 04	Dumarighat	25° 32'	86° 43'	GP,SW, LH, HH
BR06-502	Kosi	18.10.06	Dumarighat	25° 33’	86° 43’	GP,SW, LH, HH
BR06-603	Baghmati	18.10.06	Dumarighat	25° 33’	86° 43’	GP

* Major lithologies in the drainage basin upstream of sampling site.
HH: Higher Himalaya, LH: Lesser Himalaya, SW: Siwaliks, GP: Ganga plain, P: Peninsular.

** From these location two samples were collected, one representative of bank sediments and the other samples richer in clay collected from sand bars or depositing from still water condition within a few of meters from the bank.

[a] bef. confl.: before confluence with mainstream

Table 2.3: Sampling details of the Ganga River and its tributaries

Sample	River	Date	Location	Elevation	pH	Temp.	Cond.	CSI
Bhagirathi system								
RW03-5	Bhagirathi (Gangotri)	02.05.2003	N 30^0 59.642' E 78^0 56.477'	2968	-	-	-	
RW03-8	Bhagirathi (Uttarkashi)	03.05.2003	N 30^0 43.755' E 78^0 26.777'	1192	-	-	-	
RW03-9	Syansu Gad	03.05.2003	N $30^0$29.373' E 78^0 23.745'	838	-	-	-	
RW03-10	Bhilangana (Ghaushyali)	03.05.2003	-	-	-	-	-	
RW03-3	Bhagirathi (DevPrayag)	01.05.2003	N 30^0 08.729' E 78^0 35.866'	448	8.6	17.5	-	0.09
RW03-6	Glacier melt (Higher Himalaya)	02.05.2003	N 30^0 59.853' E 78^0 41.720'	2641	-	-	-	
Alaknanda system								
RW03-4	Alaknanda (DevPrayag)	01.05.2003	N 30^0 08.730' E 78^0 35.872'	455	8.1	17.5	-	-0.23
RW03-11	Alaknanda (Rudrapryayag)	04.05.2003	N $30^0$17.280' E 78^0 58.744'	629	-	-	-	
RW03-12	Mandakini (Rudrapryayag)	04.05.2003	N $30^0$17.280' E 78^0 58.744'	629	-	-	-	
RW03-13	Birhi Ganga (Trib.)	04.05.2003	N $30^0$23.823' E 79^0 23.935'	1077	-	-	-	
RW03-14	Birahi Ganga (Birhi)	05.05.2003	N $30^0$24.488' E 79^0 23.281'	1045	-	-	-	
RW03-15	Alaknanda (Birhi, before confl.)	05.05.2003	N $30^0$24.542' E 79^0 23.291'	1037	-	-	-	
RW03-16	Pindar river (Pindar Valley)	05.05.2003	N $30^0$05.290' E 79^0 27.845'	1150	-	-	-	
Ganga in Plain(2004)								
RW03-2	Ganga (Rishikesh, upstream)	01.05.2003	N 30^0 30.865' E 78^0 20.806'	335	8.1-8.6	17.9	-	0.05
BR-388	Ganga (Varanasi)	17.05.2004	N 25^0 17.840' E 84^0 00.400'	75	8.3	32.4	565	0.83
BR-309	Ganga (Patna)	07.05.2004	N 25^0 37.400' E 85^0 09.050'	45	8.1	29.0	432	0.62
BR-318	Ganga (Rajmahal)	09.05.2004	N 25^0 03.660' E 87^0 50.420'	28	8.1	30.9	322	0.44
Tributaries in Plain(2004)								
BR-346	Yamuna (Allahabad)	14.05.2004	N 25^0 25.160' E 81^0 50.190'	-	8.2	30.4	701	0.76
BR-375	Gomati (Ghazipur)	16.05.2004	N 25^0 30.350' E 83^0 08.360'	68	8.6	34.0	495	1.13
BR-342	Ghagra (Revilganj)	12.05.2004	N 25^0 49.170' E 84^0 35.090'	56	8.2	30.4	300	0.54
BR-354	Ghagra (Faizabad)	15.05.2004	N 26^0 48.770' E 82^0 12.150'	98	8.2	29.5	299	0.59
BR-363	Rapti (Gorakhpur)	15.05.2005	N 26^0 44.200' E 82^0 20.710'	81	8.3	31.8	376	0.83
BR-311	Gandak (Hazipur)	07.05.2004	N 25^0 41.290' E 85^0 11.300'	45	8.0	30.4	251	0.20
BR-334	Gandak (Barauli)	11.05.2004	N 26^0 21.600' E 84^0 44.710'	67	8.1	31.7	267	0.35

Sample	River	Date	Location	Elevation	pH	Temp.	Cond.	CSI
BR-327	Kosi (Dumarighat)	10.05.2004	N25°32.400' E 86^{0} 43.270'	38	7.9	31.4	183	-0.14
Ganga in Plain(2006)								
BR06-12-1	Ganga (Allahabad)	20.10.2006	N25° 30.474’ E81° 51.759’					
BR06-14-1	Ganga (Varanasi)	21.10.2006	N25° 17.827’ E83° 00.600’					
BR06-10-1	Ganga (Ghazipur)	19.10.2006	N25° 32.050’ E83° 11.909’					
BR06-801	Ganga (Doriganj)	19.10.2006	N25° 43.670’ E84° 49.455’					
BR06-301	Ganga (Patna)	16.10.2006	N25° 37.435’ E85° 09.209’					
BR06-401	Ganga (Barauni)	17.10.2006	N25° 22.478’ E86° 00.090’					
BR06-104	Ganga (Rajmahal)	15.10.2006	N25° 03.409’ E87° 50.229’					
Tributaries in plain 2006								
BR06-13-1	Yamuna (Allahabad)	20.10.2006	N25° 25.332’ E81° 50.255’					
BR06-11-1	Gomti (Ghazipur)	19.10.2006	N25° 30.283’ E83° 08.448’					
BR06-901	Ghaghara (Revilganj)	19.10.2006	N25° 48.783’ E84° 35.807’					
BR06-705	Gandak (Hazipur)	18.10.2006	N25° 41.326’ E85° 11.485’					
BR06-201	Son (Koilawar)	16.10.2006	N25° 33.805’ E84° 47.555’					
BR06-501	Kosi (Dhumarighat)	18.10.2006	N25° 32.704’ E86° 43.138’					
BR06-601	Bagmati (Dhumarighat)	18.10.2006	N25° 32.570’ E86° 43.240’					
Miscellaneous samples								
RW03-20	Seepage water	08.05.2003	N 30^{0}46.261' E 77^{0} 49.625'	2185	-	-	-	
RW03-21	Seepage water	08.05.2003	N 30^{0}45.809' E 77^{0} 48.921'	2373	-	-	-	
RW03-22	Seepage water	08.05.2003	N 30^{0}45.379' E 77^{0} 48.875'	2466	-	-	-	
MW03-1	Drip water	30.04.2003	N 30^{0} 21.611' E 78^{0} 80.404'	750	7.3	22.1	-	
MW03-2	Drip water	30.04.2003	N 30^{0} 21.611' E 78^{0} 80.404'	750	7.8	-	-	
MW03-3	Drip water	30.04.2003	N 30^{0} 21.611' E 78^{0} 80.404'	750	8.1	22.3	-	
RW03-7	GANG NANI (Hot spring)	02.05.2003	No GPS reading	-	-	-	-	
RW03-17	Drip water (Sahashra Dhara)	07.05.2003	N 30^{0}23.147' E 79^{0} 07.718'	862	-	-	-	
RW03-18	Sulphurous water (Sahashra Dhara)	07.05.2003	N 30^{0}23.123' E 79^{0} 07.734'	856	-	-	-	
RW03-19	Stream water (Kempty Fall)	07.05.2003	N 30^{0}29.207' E 79^{0} 02.093'	1380	-	-	-	
RW03-1	Bandal (sherki)	30.04.2003	N 30^{0} 21.163' E 78^{0} 08.400'	732	7.4	21.7	-	

In addition, time series water sampling for the Yamuna at Allahabad and the Ganga after the confluence with Yamuna at Allahabad at biweekly intervals over a period of 10 months was also done during 2004-2005. Further, a few other specific samples, mainly from seepage, drip and spring waters from the Himalayan basin of the Ganga, precipitated carbonates from locations adjacent to drip water and a few ground water samples close to the river banks were also collected. The details of sampling are discussed below. The sampling locations are listed in the Tables-2.2 and 2.3.

2.4.1 River and Groundwater

The parameters measured in the dissolved phase of river and ground waters are major ions, silica, $^{87}Sr/^{86}Sr$ and Sr. The sampling locations (latitude and longitude) were determined mainly using global positioning system. At some locations during the 2003 sampling GPS was unable to track the satellites and hence these locations are based on maps. The sampling was done with the help of boats or from bridges from mid channel of the rivers to avoid anthropogenic and local influences. For major ions and Sr isotopes, samples were collected using clean polyethylene containers.

The water was filtered at the sampling site through 0.2 μm Nucleopore filters and stored in two precleaned polyethylene bottles of 500ml capacity. The samples were brought to the laboratory within a week; one of the bottles was acidified with high purity HNO_3 to pH~2 for the analysis of Na, K, Ca, Mg, Sr, and Sr isotopes. The second bottle was stored un-acidified for analysis of anions (Cl, F, NO_3 and SO_4). Another aliquot of unfiltered river water was collected and stored in ~120 ml bottles for alkalinity measurements.

In addition, shallow ground water samples were collected from wells at ~200m away from the banks of the Yamuna and the Ganga at Allahabad. In addition to the above river water samples, a set of time series water samples was collected at biweekly intervals over a period of ~10 months from the Yamuna (at Yamuna bridge, Allahabad) and the Ganga (Chhatanag, Allahabad) after the confluence with the Yamuna. The samples were collected in 5 liter bottles and kept as such at Allahabad. At the end of the sampling period, two aliquots, one of one liter and the other of 120 ml from each biweekly sample were gently transferred to polypropylene bottles at site. The particulate matter settled at the bottom of 5L bottle was separated by decanting the supernatant water. All the water and particulate matter samples were brought to the laboratory. The water samples in 1 liter bottle were filtered with 0.2 µm Nucleopore filters, split into two aliquots; one was acidified as discussed above. The samples were analysed as detailed later.

2.4.2. Sediments and Suspended Particulates

Sediment samples from the Ganga mainstream and its major tributaries in both the Himalaya and the plain were collected from their banks within a few meters of water. In addition, sediment samples richer in fine fraction were also collected, generally from sandbars exposed in the mid-channel of the rivers. The sampling spanned the entire stretch of the Ganga, from its source at Gangotri to near its outflow at Farakka (Figs-2.1a, b). The sampling was done during May 2003 (summer) from the Himalayan sector and during May 2004 (summer) and October 2006 (monsoon/post monsoon) from the plain. A single sample of the Ganga sediments was collected from Kanpur in May 2005. The repeat sampling in the plain was done to assess the temporal variability in the chemical and isotopic composition of sediments along the Ganga mainstream and the role of tributaries in contributing to this variability. During sampling, wherever possible, 5-6 samples were collected from an area of ~ 500 m × 500 m and were mixed and homogenized at site to yield a representative sample of sediment from that location. Sediments samples (~1kg) after collection were stored in polythene bags and were taken to laboratory. Suspended matter samples were recovered from ~10 liters of water by settling (~2 weeks). This water sampling was done during October 2006, when the suspended matter concentration is generally high due to monsoon. After settling, the clear supernatant water was decanted and the slurry containing suspended matter was transferred to a beaker and dried in an oven. The dried material was powdered using agate mortar and pestle and used for various analyses.

2.4.3 Other samples

In addition to river and ground water samples, drip and spring waters from the upper catchment of the Ganga in the Himalaya, freshly precipitated carbonates from the regions near drip water, and gastropods and calcium carbonate nodules, locally called *kankars* (Sarin et al., 1989; Pal, 1994, 2003; Agarwal et al., 1992; Singh, 2005; Sinha et al., 2006) were also collected as a part of this study. The drip waters are either from caves or from fissures (seepage) exposed on surface. Near to these drip/seepage waters there were precipitated carbonates, these were also sampled for this study. The gastropods were sampled from the Ganga river and the kankar (impure carbonates) was collected from the bank of the Ganga at Allahabad (after its confluence with Yamuna).The sample was collected from a section ~1-2 m below the sediment surface.

2.5 Analytical Techniques

The analytical techniques used depended on the type of samples being analysed and the parameters being measured. Among the various analytical techniques used in this study, significant efforts were put in establishing chemical procedures for extraction and purification of Sr and Nd from riverine suspended and particulate phases and their isotopic analysis by Thermal Ionization Mass Spectrometry (TIMS). This was done as a part of setting up of a new mass spectrometric facility at PRL, Ahmedabad. Nd extraction procedures and its mass spectrometry were established for the first time in our laboratory and are based on those available in literature (Richard et al., 1976; Alibert, et al.,1983). These chemical procedures and associated mass spectrometric analyses are described in some detail in this section, the methods used for the determination of elemental abundances in water and sediments are mentioned only briefly as they are based on available procedures in our laboratory (Sarin et al., 1989; Dalai, 2001; Das, 2005).

2.5.1 Water Samples

(a) pH, temperature and electrical conductivity:

pH and electrical conductivity (EC) of river waters were measured at site using a multi-purpose kit (Model: Multiline 7000). The pH probe was calibrated with freshly prepared buffer solutions of pH 4.0 and 9.2, and the EC probe with 0.01 M KCl solution prior to making the measurements. The precision of pH measurements is better than 0.1 units and that of EC measurement is better than 10 μS cm^{-1}. Temperature of river waters was measured by a portable thermometer (MA line), with precision better than 0.1 °C.

(b) Major ions and dissolved silica:

Alkalinity measurements were done on unfiltered water samples generally within about two weeks of collection by acid titration with dilute HCl of known strength (~0.01M) using an auto-titrator (Metrohm 702 SM Titrino) with a glass electrode. Prior to measurements the samples were kept undisturbed for several days to settle the particulates. A known aliquot of supernatant water was pipetted for alkalinity measurements. In the time series samples, the alkalinity measurements were made at the end of sampling, therefore in some cases the delay between collection and measurement were several months. The measurement was based on fixed end point method corresponding to two end points at pH values of 8.3 and 4.3 for CO_3^{2-} and total carbonate species (HCO_3^- and CO_3^{2-}). Cl, F, NO_3 and SO_4 were determined by ion chromatography (Dionex series 2000i/SP) in filtered, un-acidified samples (Dalai, 2001; Rastogi, 2005).

The system was calibrated using standards prepared from analytical grade salts (NaF, NaCl, Na_2SO_4 and KNO_3). The separation of ions (F, Cl, NO_3 and SO_4) was done on AS14A column using an appropriate eluent. In some cases samples were suitably diluted with distilled water to make the concentrations of the ions within the range of measurement.

Si measurements were done using a spectrophotometer (Model Beckman 26) based on the Mo-blue method (Strickland and Parson, 1972; Das 2005) at wavelength of 810 nm. The working Si-standard was prepared by dissolving Na_2SiF_6 in double distilled water. The analyses were done in filtered, un-acidified aliquots. In one sample, Si measurement was checked in both the acidified and un-acidified splits; they yielded Si concentration within the analytical precision of ~2%.

Among the cations, Na and K measurements were done in filtered un-acidified samples using flame-AAS (Perkin Elmer Model 4000). The calibration was done using Merck® standard solutions. The accuracy of measurement was checked by measuring solutions of known concentrations prepared from analytical grade salts (NaCl and KCl). Ca and Mg measurements were done in filtered, acidified splits by inductively coupled plasma-atomic emission spectrometry (ICP-AES; Jobin Yvon, Model 38S). The measurements were done by sequential scanning of the emission line at wavelengths of 279.806 nm (Mg) and 422.673 nm (for Ca). Ca and Mg standards were made by dissolving pure anhydrous $CaCO_3$ and Mg metal in acids. Ca and Mg were also measured at flame-AAS (Perkin Elmer Model 4000). The two measurements were consistent within ±5%. In some of the time series water samples (un-acidified), the major ions (Na, K, Ca, Mg, Cl, and SO_4) were measured by ion chromatography with analytical precision better than 2% (Table 2.4).

The reproducibility of major ion measurements was checked by repeat analyses. The results expressed as coefficient of variation is given in Table-2.4. Based on replicate analyses, the coefficients of variation were calculated using the formula.

$$CV(\%) = \left(\frac{1}{2n} \sum \left(\frac{d_i}{x_i} \right)^2 \right)^{\frac{1}{2}} \times 100 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (2.1)$$

where d_i is difference between the duplicates with mean x_i and n is the total sets of duplicates. Reproducibility of measurements for dissolved silica and major ions were better than 2.5% except F (4.3%) and NO_3 (3.5%).

Two numbers are given for the alkalis and alkaline earth elements in Table-2.4. For Na, K and Mg, the first column is based on ion chromatograph, and the second AAS. For Ca it is based on ion chromatograph and ICP-AES and for Sr, AAS and TIMS. Silica data is based on spectrophotometric analysis. For anions, it is based on ion chromatograph, except for alkalinity which was measured by titration. The accuracy of measurements was checked by Merck standards of known concentrations.

Table-2.4: Coefficient of Variation for major ions and silica in river waters

Ion/Species	**Coefficient of Variation (%)**	
Na^+	1.0	1.6
K^+	1.4	1.0
Mg^+	1.3	0.5
Ca	1.6	2.6
Sr	3.4	0.4
F	4.3	-
Cl	2.2	-
SO_4	1.5	-
NO_3	3.5	-
HCO_3	0.4	-
SiO_2	0.4	-

(c) Sr and $^{87}Sr/^{86}Sr$ isotopes in water samples:

Sr concentration in water samples was measured in the filtered, acidified samples (May 2004) using graphite furnace AAS. Calibration of the instrument was done with Merck standard solutions. In some of the water samples (October 2006), Sr concentration was determined by isotope dilution (using ^{84}Sr tracer) by thermal ionization mass spectrometry (TIMS). For Sr isotope measurements, typically about 100-150 ml of filtered, acidified river water was taken in cleaned FEP beakers and evaporated to near dryness. The volume of water used for Sr isotope analysis was decided based on Sr concentration in water such that at least 5 µg of Sr was available for isotope measurements. To the residue, about ~1 ml of HNO_3 (Seastar chemicals®) was added to oxidize organic matter and dried completely. The residue was taken in 1.5 ml 2N HCl. The solution was centrifuged and from the clear solution Sr was separated by ion exchange chromatography using Dowex 50X8 (200-400 mesh) in 2N HCl medium (Dalai, 2001; Singh et al., 2006).

In a few water samples, Sr was separated using Eichrom® Sr specific resin (50-100μm; Horwitz, et al., 1992; Pin and Bassin, 1992; Pin et al., 1994; Rai and Singh, 2007). The Sr specific resin was conditioned with 3N HNO_3. In this method 4 -10 ml of water was dried; the residue was taken in 3N HNO_3 medium and loaded on ~200 µl of resin contained in 10 ml capacity columns. The Sr from the resin was eluted with milli Q water. The pure Sr fraction was dried, dissolved in a few µl of 2N HCl and loaded with H_3PO_4 on degassed and oxidized high purity Ta or Re filaments. The Sr isotope measurements were carried out on TIMS in multi collector mode. Several repeat measurements were made to check the reproducibility of results.

The accuracy of measurements was checked by analyzing USGS standard (G-2) solution. The measured $^{87}Sr/^{86}Sr$ is 0.709785±0.000008 (n=1) with Sr concentration 460 ± 8 ppm. This compares well with the reported value (USGS certificate of analysis for reference material G-2) of 709785±0.000058 (n=3) and Sr concentration 478±2 ppm. The precision for Sr measurements by graphite furnace AAS and TIMS are 3.4 and 0.4% respectively.

2.5.2 Sediments

(a) Major elements

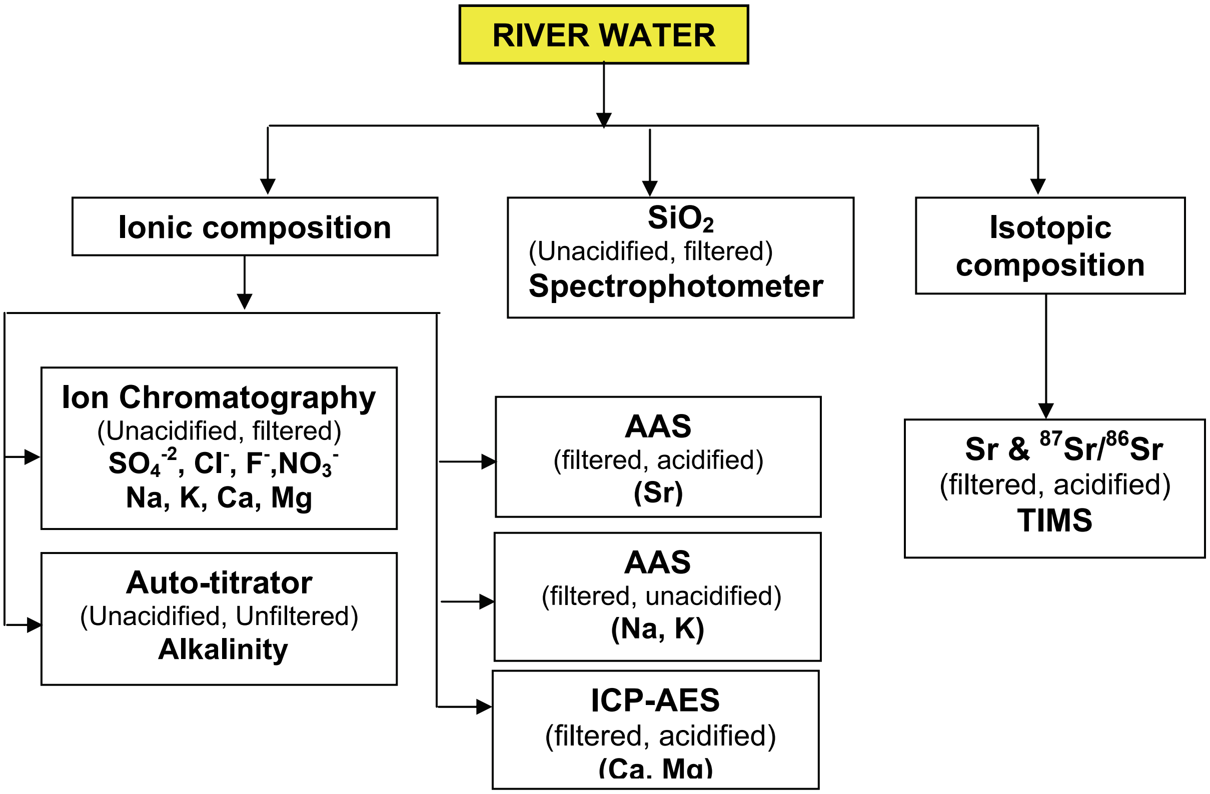
The sediments stored in plastic bags were brought to the laboratory for analysis. In the laboratory, a fraction of the sediments (~250g) was transferred to clean glass beakers and dried at ~50°C for 2~3 days. These dried sediments were powdered using an agate ball mill and sieved through nylon sieves of 100 µm size. The sieved samples were stored in plastic containers. Care was taken to avoid any metal contact during powdering and sieving. A known weight of finely powdered (≤100 µm) sediments was taken in quartz crucibles and combusted at ~600 °C to oxidize organic matter. About 0.5 g of ashed samples were taken in PTFE dishes and digested with HF to remove silica. The residues were brought to solution by repeatedly treating with HCl-HNO_3 mixture. The solutions were made to 50 ml in 0.2N HNO_3. Few samples were digested in duplicate to check the overall precision of analyses. Along with the samples, USGS reference standards W-1 and G-2 (for Sr and ^{87}Sr/^{86}Sr) were also processed to check the accuracy of analyses.

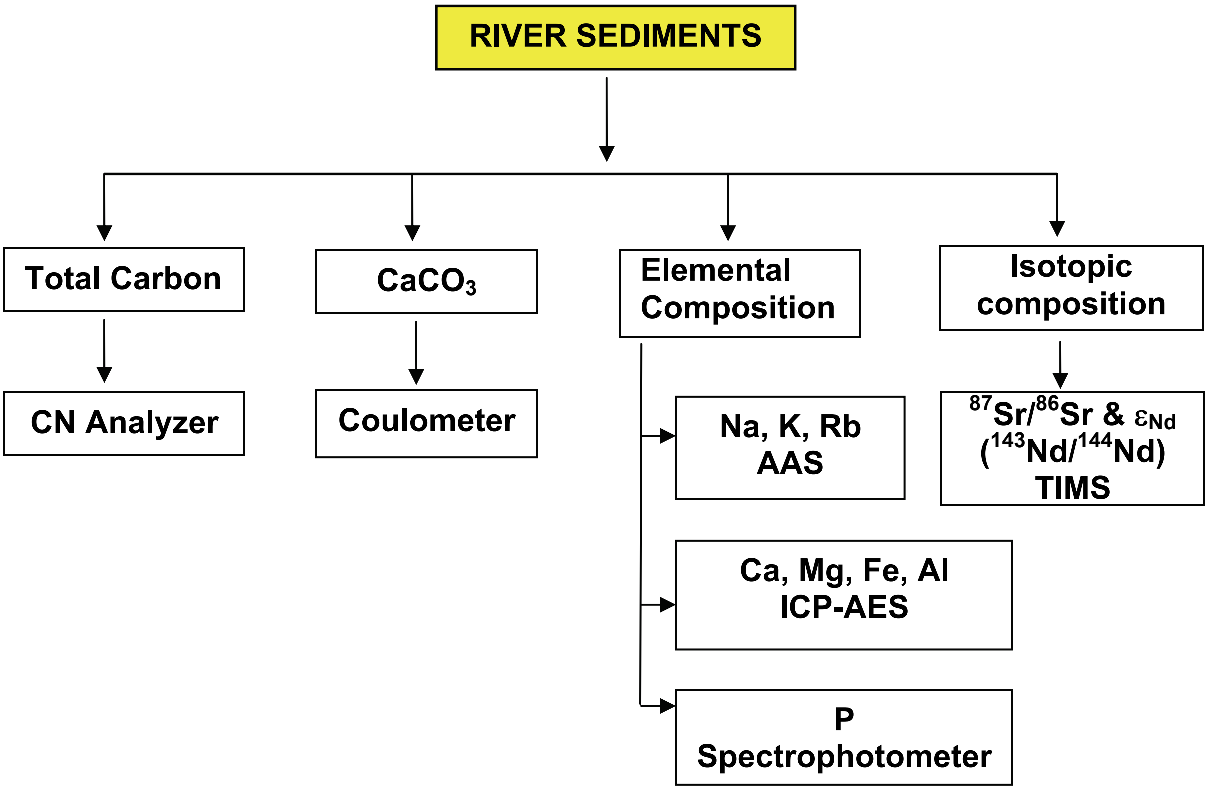
Table 2.5: Results of elemental analyses in USGS reference material W-1

Element	Technique	Measured (wt%)	SD	Reported^{+} (wt%)	SD
Ca	ICP-AES	7.98	0.26	7.86	0.09
Mg	ICP-AES	4.02	0.08	3.99	0.08
Na	AAS	1.68	0.07	1.60	0.04
K	AAS	0.55	0.03	0.53	0.02
Fe	ICP-AES	7.76	0.26	7.71	0.16
Al	ICP-AES	7.75	0.26	7.88	0.14
P (ppm)	UV-VIS Spectrophoto.	581	-	580	40
Rb (ppm)	AAS	22	2	21	0.3

$^{+}$ USGS certificate of analysis; Potts et al., 1992

SCHEMES OF ANALYSES





Na, K and Rb were measured in the solution by Flame-AAS (Multi element standards (Merck) were used for calibration and were checked by internal lab standard prepared from their respective salts). For measurements using AAS, all samples were suitably diluted to bring them into linear range of absorbance-concentration relation. Other major elements (Ca, Mg, Fe and Al) were measured using ICP-AES. P was measured by molybdenum blue method (wavelength 885 nm) using a spectrophotometer (Strickland and Parson, 1972; Das, 2005). The precision of measurements based on the repeat measurements for various elements are presented in Table-2.5 and given in the Fig-2.5. The measured values in USGS standard W1 show excellent agreement with those reported in literature (Potts et al., 1992).

(b) $CaCO_3$ and organic carbon

The carbonate content in river sediments was measured using a coulometer (UIC Coulometer; Model 5012). The instrument was calibrated with Na_2CO_3 solution prepared from analytical grade reagent. CO_2 was liberated from solution/sediments by treating the samples with 40% H_3PO_4 at 85°C for 10 minutes in an extraction cell. About 100 mg of dry sample powder was taken for analyses.

Table 2.6: Results of repeat analyses of major elements in sediments

Sample ID	Ca %	Mg %	Na %	K %	Fe %	Al %	P (ppm)	Rb (ppm)
BR-306	2.27	0.84	1.09	1.51	2.17	3.91	682	86
BR-306(D)	2.33	0.85	1.11	1.54	2.17	3.92	714	87
BR-330	0.71	0.43	1.37	2.02	1.79	4.76	377	114
BR-330(D)	0.69	0.41	1.32	2.02	1.82	5.00	373	114
BR-365	1.85	0.41	0.63	1.22	1.37	2.70	355	63
BR-365(D)	1.88	0.42	0.64	1.21	1.39	2.69	355	64

BR-344	3.18	2.34	0.36	3.68	6.45	10.94		249
BR-344(D)	3.15	2.30	0.35	3.71	6.68	11.08		250
BR-383	1.78	2.15	0.24	2.83	7.80	11.62		200
BR-383(D)	1.72	2.03	0.24	2.82	8.21	11.80		203
BR06-205	0.46	0.23	0.41	1.90	0.62	2.17		82
BR06-205(D)	0.50	0.26	0.38	1.91	0.63	2.14		80
BR06-701	5.79	1.13	0.91	1.51	2.02	3.99		87
BR06-701(D)	5.57	1.14	0.90	1.50	1.86	3.86		85
BR06-SL1	1.31	1.56	0.74	2.90	4.49	8.15		196
BR06-SL1(D)	1.40	1.57	0.75	2.90	4.30	8.14		198
BR06-SL6	1.16	1.43	0.83	3.03	4.41	8.33		220
BR06-SL6(D)	1.20	1.41	0.80	3.00	4.11	8.05		216

Table 2.7: Coefficient of variation for different elements in sediments+

Element	Technique	Coefficient of Variation (%)
Ca	ICP-AES	2.9
Mg	ICP-AES	3.5
Na	AAS	2.3
K	AAS	0.7
Fe	ICP-AES	3.2
Al	ICP-AES	1.7
P	Spectrophoto.	1.9
Rb	AAS	1.0

+ based on nine pairs of repeat measurements except P, for which it is based on three pairs.

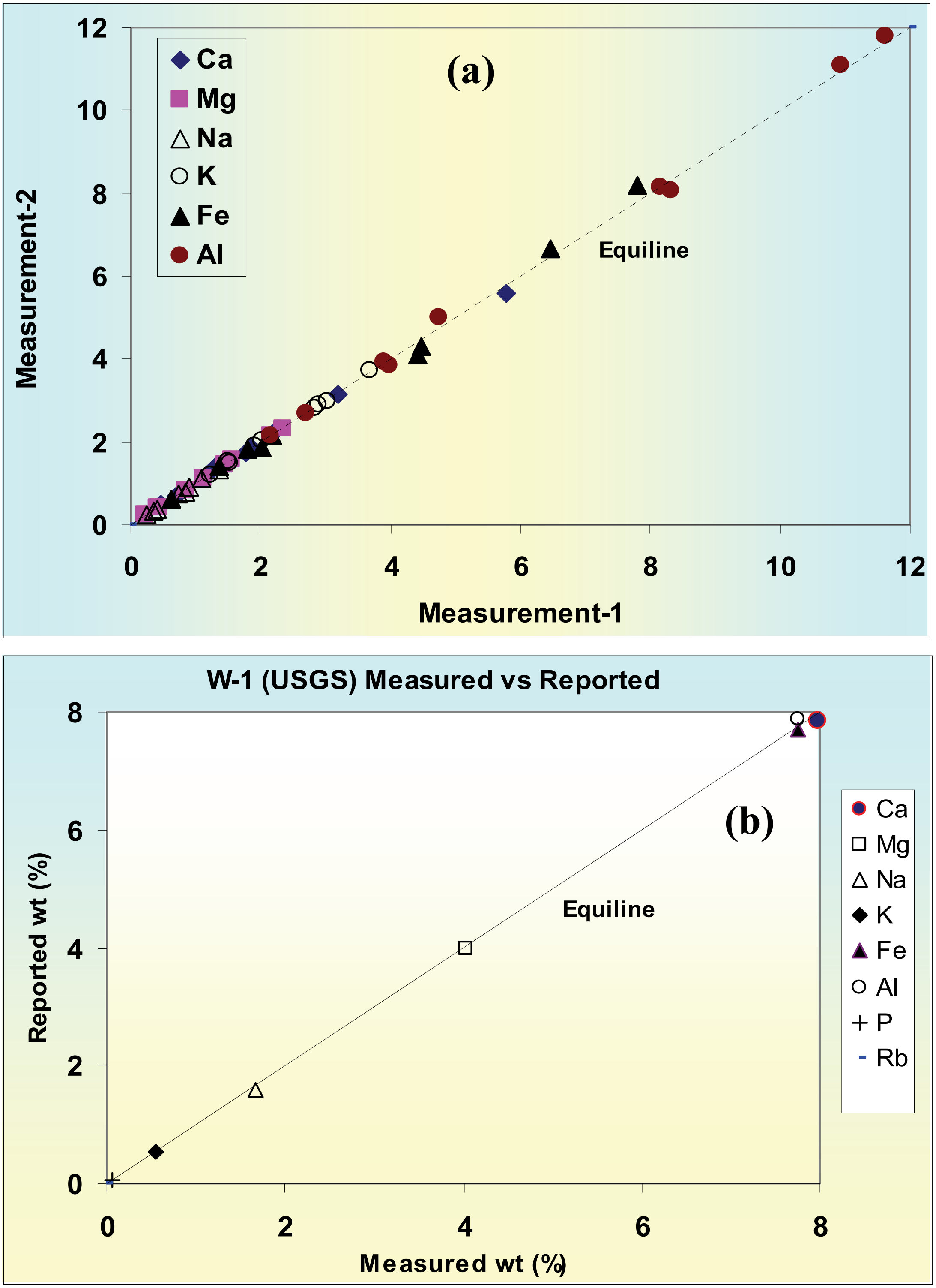


Fig 2.5: Results of (a) repeat measurements (wt. %) of different elements in sediment samples. The repeat measurements show excellent agreement (b) measured concentration of various elements in USGS rock standard W1 plotted against those reported in literature (Potts et al., 1992).

The CO_2 liberated from the sediment sample was purified through a column of silica gel and anhydrous $MgClO_4$. The purified CO_2 was measured in the coulometer titration cell.The precision of inorganic carbon (IC) measurements based on replicate analyses and standard solutions over wide range of concentration (<0.1% to 5.6%) of IC was ~ 2.5% (Table-2.8). Total carbon (TC) was measured using FISONS NA1500 CN elemental analyzer (Fisons Inc., Italy; Sarin et al., 1997). For this, 10-30 mg of dried sediment sample was packed in aluminum cups and was introduced into the combustion tube of an auto sampler for carbon and nitrogen analysis.

Table-2.8: Replicate measurements of inorganic carbon (IC)and total carbon (TC) in river sediments

Sample ID	**IC (%)**		**TC (%)**	
	Meas (1)	Meas (2)	Meas (1)	Meas (2)
RS03-27	5.61	5.65	7.23	-
RS03-31	1.21	-	1.29	1.26
BR-306	0.65	0.64	0.67	-
BR-330	0.03	0.03	0.08	-
BR-343	0.91	0.91	1.08	-
BR-348	0.50	-	0.61	0.63
BR-371	0.99	0.98	1.18	-
BR-378	0.34	0.34	0.49	-
BR-382	0.22	0.23	0.32	-
SLG-10	0.61	-	0.68	0.70
SLG-16	0.18	0.17	0.66	-
SLY-14	1.12	-	1.82	1.84
SLY-15	1.15	1.16	1.88	1.91
SLG-17	0.18	-	0.60	0.62

A three-point calibration line was made using the Deer River Shale containing 2.53 wt.% carbon as the reference material (Krom and Berner, 1983; Sarin et al., 1997; Bhushan et al., 2001). C_{org} content is calculated by the difference between total carbon and carbonate carbon contents in the sample (Verardo et al. 1990).

C_{org} = TC - IC……………………(2.2)

where TC is the total carbon and IC is the inorganic carbon (from carbonates). The analytical precision for measurements of $CaCO_3$ and total carbon are 2.1% and 1.6% respectively (Table-2.8).

(c) Isotopic Measurements: Mass Spectrometry

Sr, and Nd isotopes were measured in different samples (river water, sediments and carbonates) using a new generation solid source mass spectrometer (Micromass Isoprobe-T) set up at the Physical Research Laboratory (PRL), Ahmedabad. The mass spectrometer was procured at PRL during the course of this thesis work. Part of my work involved working with Dr. Sunil K. Singh to establish procedures for the extraction of Sr and Nd from various samples and measurement of their isotopic composition using the mass spectrometer. There was considerable expertise for Sr isotope measurements at PRL whereas the Nd measurements were made for the first time at PRL as a part of this work. The Nd separation from matrix and its measurement procedure is adapted from literature (Alibert et al., 1983; Richard et al., 1976) and is discussed briefly in section (d).

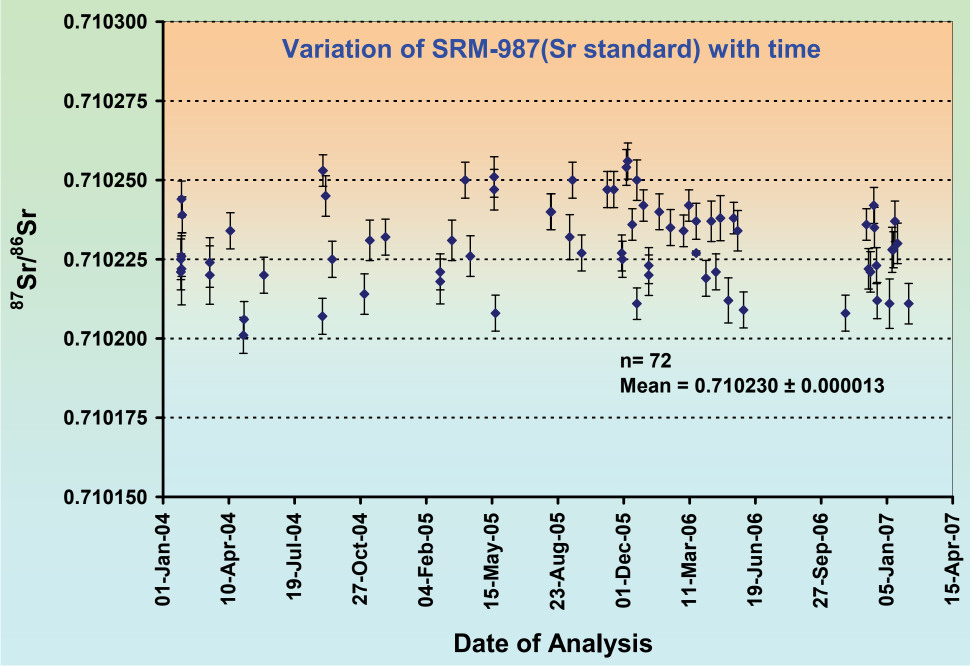
The Sr and Nd isotope measurements were made in static multi collector mode. Mass fractionation corrections for Sr and Nd were made by normalizing $^{86}Sr/^{88}Sr$ to 0.1194 and $^{146}Nd/^{144}Nd$ to 0.7219 respectively. Internal precision for both these ratio measurements were better than 10 ppm ($1\sigma_{\mu}$). During the course of the study, SRM987 Sr and JNdi Nd standards were repeatedly measured, these yielded $^{86}Sr/^{88}Sr$ values of 0.710230±0.000013 (1σ, n = 72) for $^{86}Sr/^{88}Sr$ and 0.512105±0.000006 (1σ, n =9) for $^{143}Nd/^{144}Nd$ respectively, (Fig-2.6) well within the recommended values. Several repeat measurements of Sr isotopes of the Arabian Sea water and in a coral sample from the Bay of Bengal were also made to check the precision and accuracy of Sr measurements (Table-2.9).

(d) Sr and Nd isotopes in sediments:

The Sr and Nd concentration and isotopic measurements were carried out in the *silicate* fraction of total sediments and their < 4 μm size separates. The < 4 μm fraction was separated from bulk (total) sediments by settling in water.

The abundance of < 4 μm fraction in sediments from the higher reaches (i.e., upstream of Rishikesh, Fig-2.1a) was very low and hence in many of these samples only bulk sediment analyses could be made. In the laboratory, the dried sediment samples were powdered (≤ 100μm) and used for analysis. The major element concentrations were made in total sediments whereas the Sr and Nd isotope measurements were made in their silicate fraction. For isotopic measurements, a known weight of powdered sample (~ 1 gram) was leached using 0.6 N HCl with intermittent ultrasonic treatment at 80°C to remove carbonates. The slurry was centrifuged; the residues washed with water, dried and ashed at ~ 600°C to oxidize organic matter.

A known weight (about 100 mg) of the carbonate and organic matter free sediments were transferred to 7 ml Savillex® vials and brought to complete solution using ultra-pure HF and HNO_3 (Seastar Chemicals®) in presence of ^{84}Sr and ^{150}Nd tracers. Sr and REEs were separated from the solution following standard ion exchange procedure (Singh and France-Lanord, 2002; Singh et al., 2008). From the REE fraction, Nd was separated using HDEHP coated Teflon powder (Richards et al., 1976; Alibert, 1983; Singh et al., 2008). The purified Nd was loaded on the outer Tantalum filament of the triple filament assembly. Sr and Nd concentrations and their $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ were measured using Isoprobe-T Thermal Ionization Mass Spectrometer (TIMS). Nd isotopes systematics in sediments is expressed in ε_{Nd} units (Faure, 1986). To check on the precision and accuracy of $^{87}Sr/^{86}Sr$ analyses sea water and coral samples were analysed. The results are given in Table-2.9. The samples Sea water-1, 2,



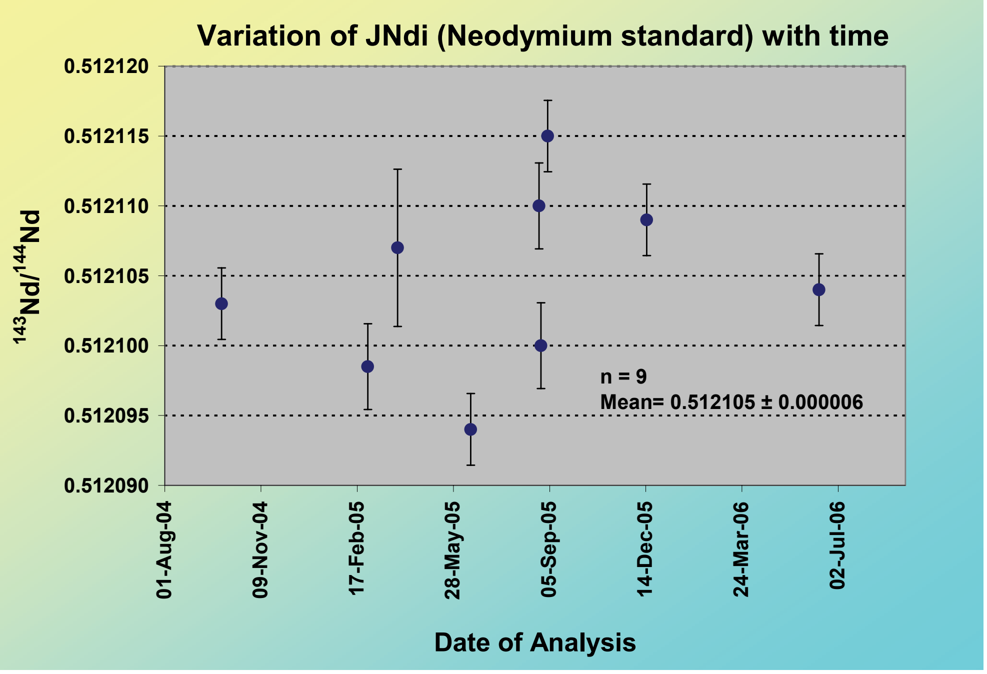


Fig-2.6: Temporal variation in ^{87}Sr/^{86}Sr and ^{143}Nd/^{144}Nd measured in standards.

3 and 4 are all aliquots of the same seawater sample processed separately. The sample Sea water-1R is re-run of the same Sr load of Sea water-1. Three coral samples from the Bay of Bengal were powdered and processed for Sr. The data show good reproducibility. Several Sr and Nd total procedural

blanks were measured along with the samples; average blank for larger (~100 ml) water and sediment sampling was 1.8 ±0.77 ng; (n=11) whereas for Nd it was ~300 pg. For these determinations of Sr procedural blanks, 100 ml Milli-Q water was used in place of river water and processed with the same quantity of reagents as used for the samples.

Table- 2.9: ^{87}Sr/^{86}Sr in Arabian Sea water and corals

Date of Run	**Sample**	**^{87}Sr/^{86}Sr**	$\pm(1\sigma_{\mu})$
17-Feb-04	Sea Water-1	0.709140	0.000006
26-Feb-04	Sea Water-1R	0.709150	0.000008
17-Feb-04	Sea Water-2	0.709129	0.000009
23-Feb-04	Sea Water-3	0.709172	0.000008
24-Feb-04	Sea Water-4	0.709154	0.000008
	Mean	0.709149	
	SD (N=5)	0.000016	
03-Jan-07	Coral SM-1	0.709154	0.000007
03-Jan-07	Coral SM-3	0.709150	0.000007
03-Jan-07	Coral SM-4	0.709151	0.000007
	Mean	0.709152	
	SD (n=3)	0.000002	

Sr blanks for the Sr specific resin used for smaller volume water samples range from 300 pg to 600 pg. ^{87}Sr/^{86}Sr was measured in three blanks which yielded value of ~0.7118 ± 0.0002 (n =3). These Sr blanks are about three orders of magnitude lower than typical total Sr and Nd analysed and hence no corrections were made for blanks.

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.

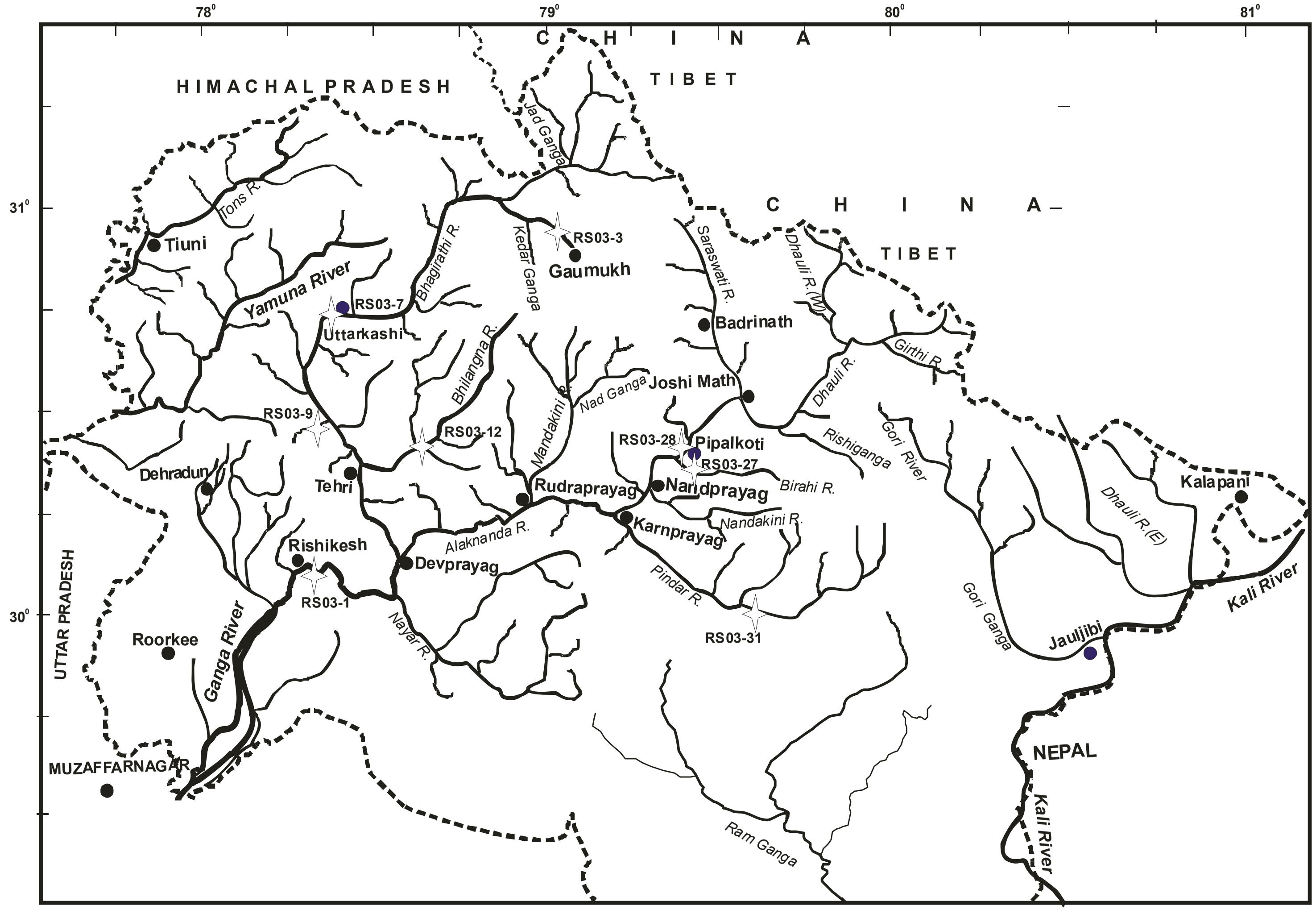


Fig- 3.1: Sampling locations of sediments from the Ganga basin in its Himalayan drainage.

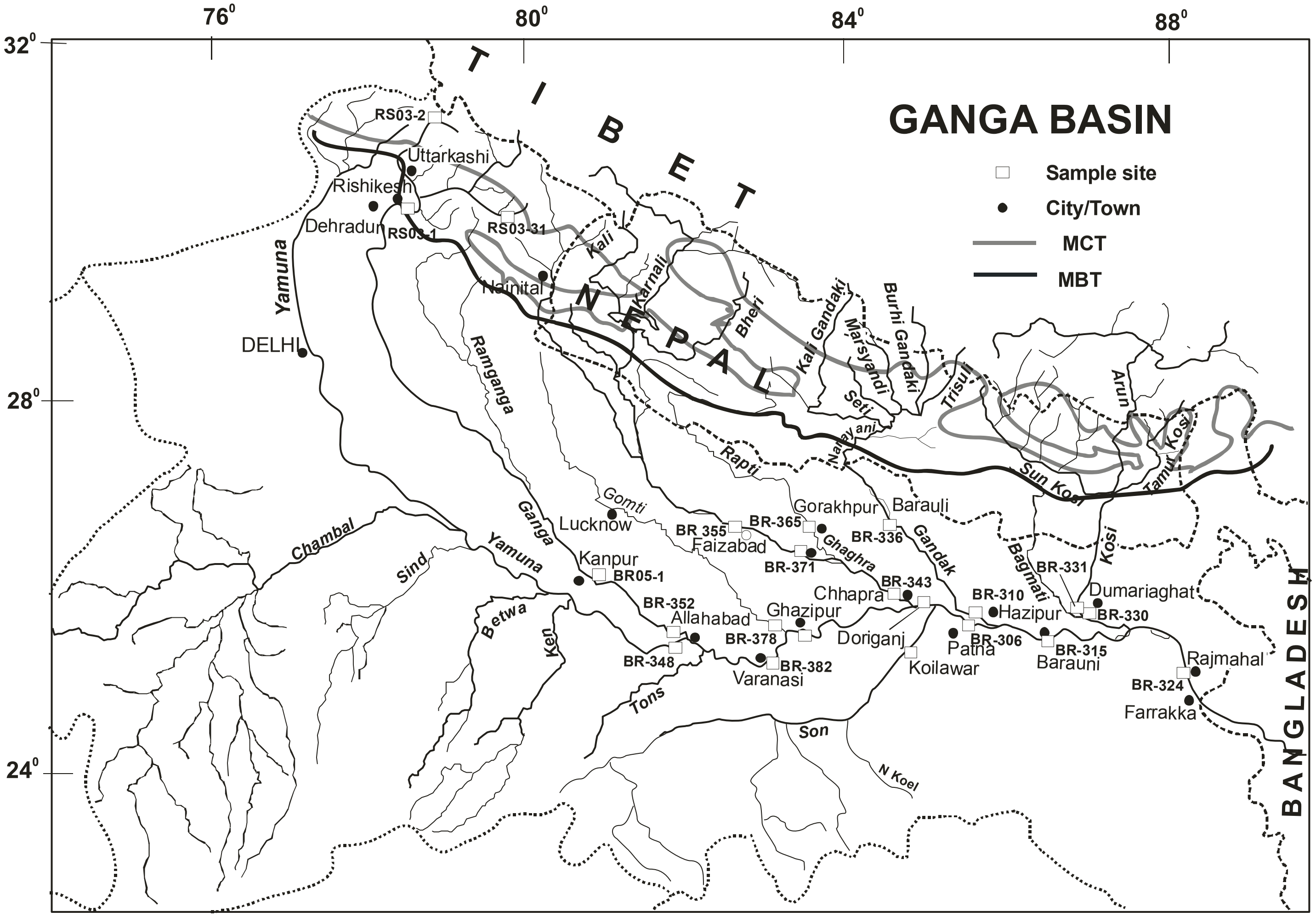


Fig- 3.2: Sampling locations of sediments from the Ganga basin in plain. The locations of samples collected in 2004 are marked in the map. Bank sediments from the Ganga mainstream and its major tributaries were collected all along the course of the Ganga, from its source (Gangotri) to Rajmahal near the 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 % ($\pm 2\sigma$) and <20 ppm (($\pm 2\sigma_{\mu}$) 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 (n=10)	9

Δ (%) relative to 2004

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 (n=10)	0.0056

* Before confluence

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).

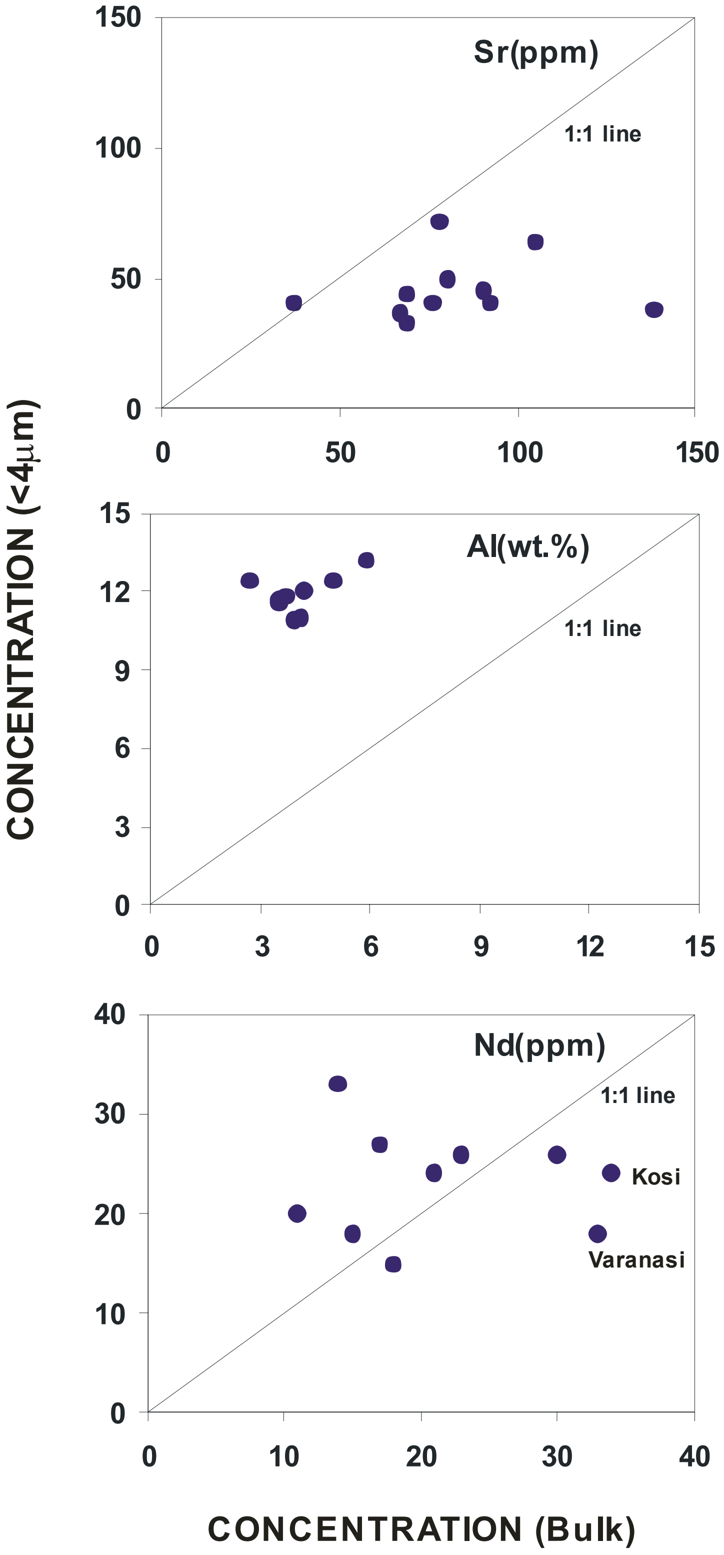


Fig-3.3: Scatter diagram of Sr, Al and Nd abundances in silicates of bulk sediment and their <4 μm fraction. It is seen that Sr in <4 μm fraction is less than that in bulk, whereas Al and Nd (in majority of samples) are enriched in <4 μm fraction.

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.

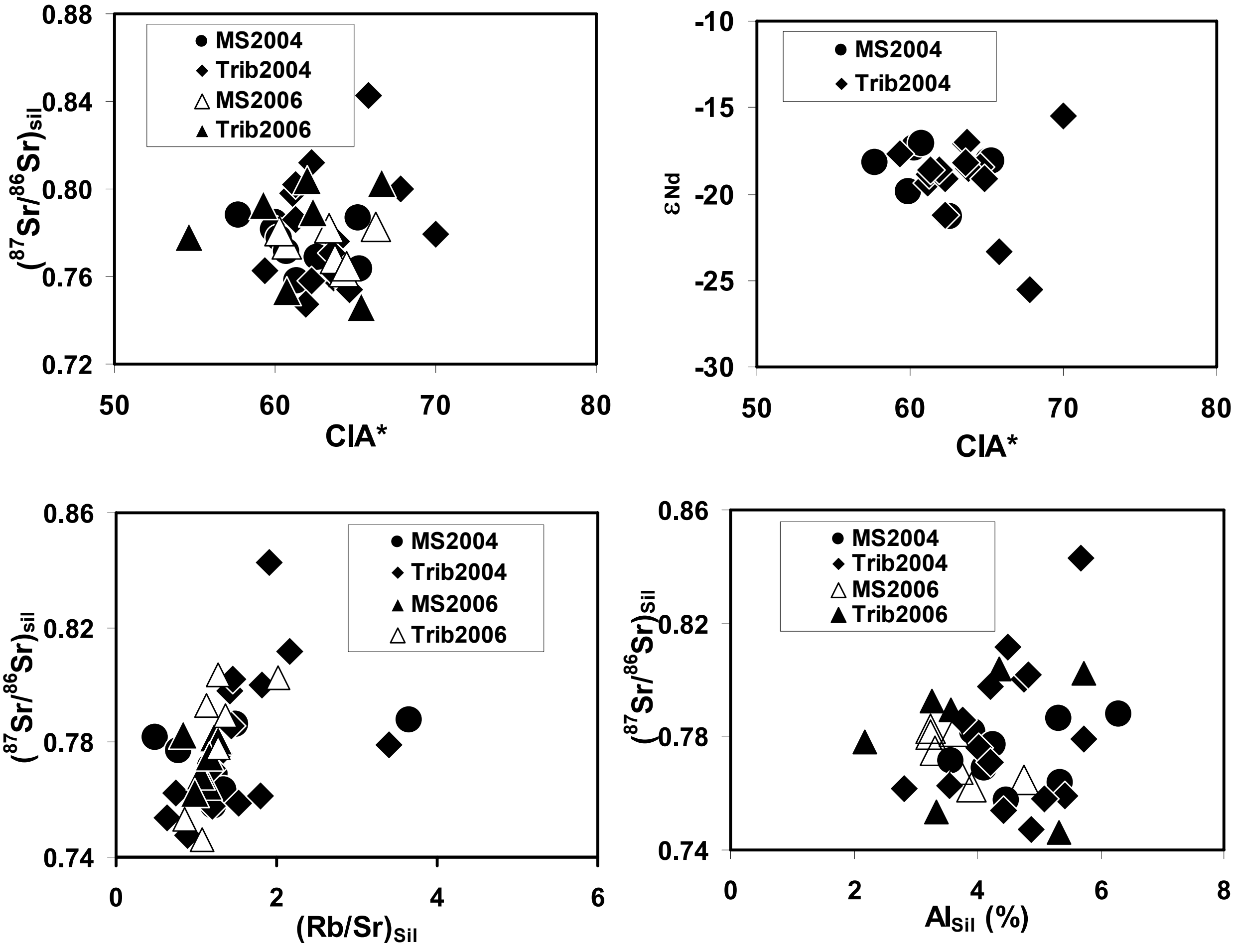


Fig-3.4: Scatter plots of CIA* (Al_2O_3*100/(Al_2O_3+Na_2O+K_2O)) in bank sediments with their $^{87}Sr/^{86}Sr$ and ε_{Nd} values. The bottom two plots are of $^{87}Sr/^{86}Sr$ vs $(Rb/Sr)_{sil}$ and $^{87}Sr/^{86}Sr$ vs Al_{sil}. The measured Al and Rb in the bank sediments are corrected for carbonate 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**
Higher Himalaya				
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
Lesser Himalaya				
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
Siwaliks	0.72-0.76	0.738±0.018	-19 – -15	-17.2±1.2
Peninsular Drainage				
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).

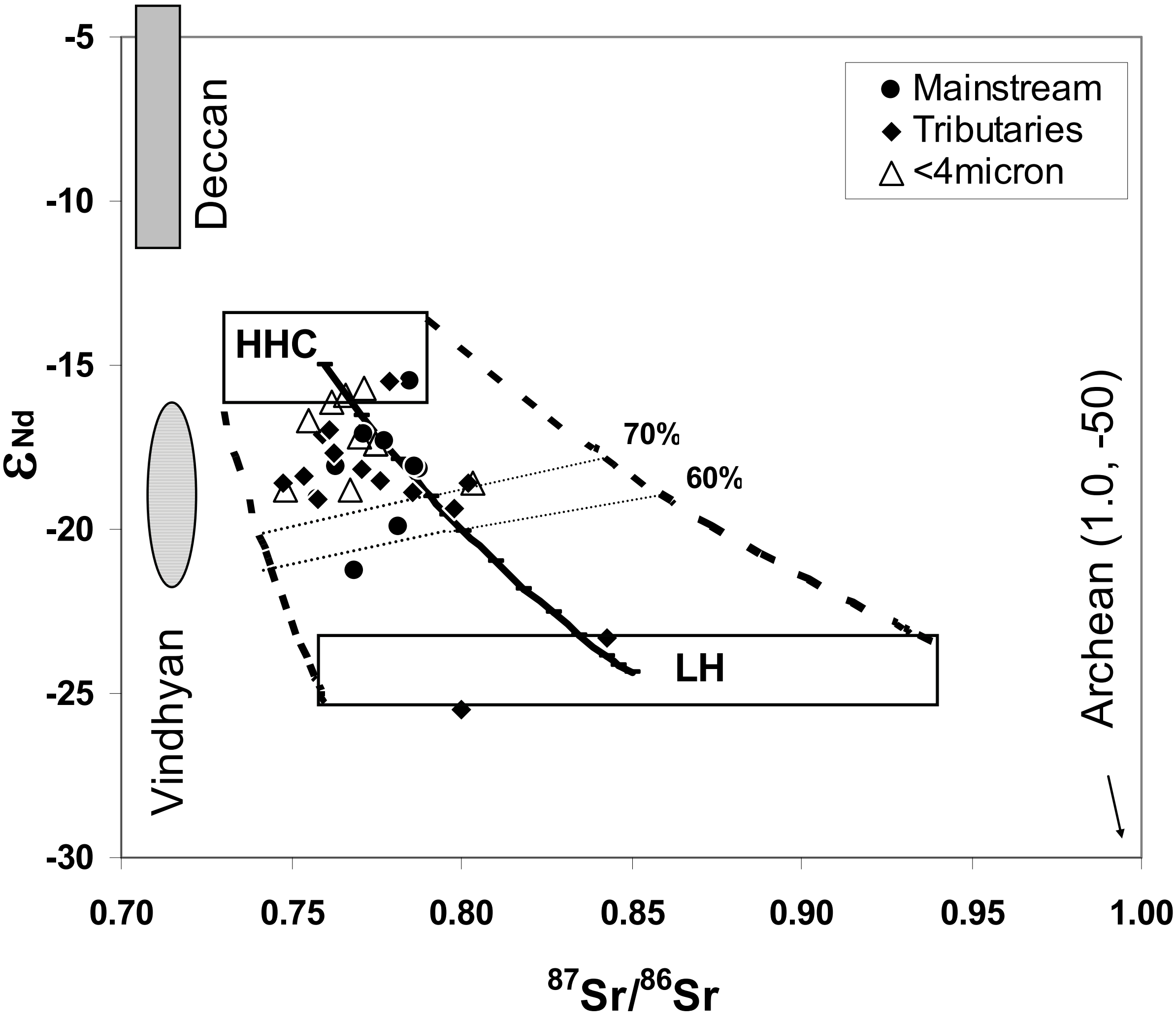


Fig- 3.5: Two isotope system plot, $^{87}Sr/^{86}Sr$ and ε_{Nd}, in silicates of bulk sediments and their <4 μm fraction. The range in isotopic composition of potential sources of sediments to the Ganga system is also given (see Table-3.6). Plot shows that the isotope ratios of most of the sediment samples 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.

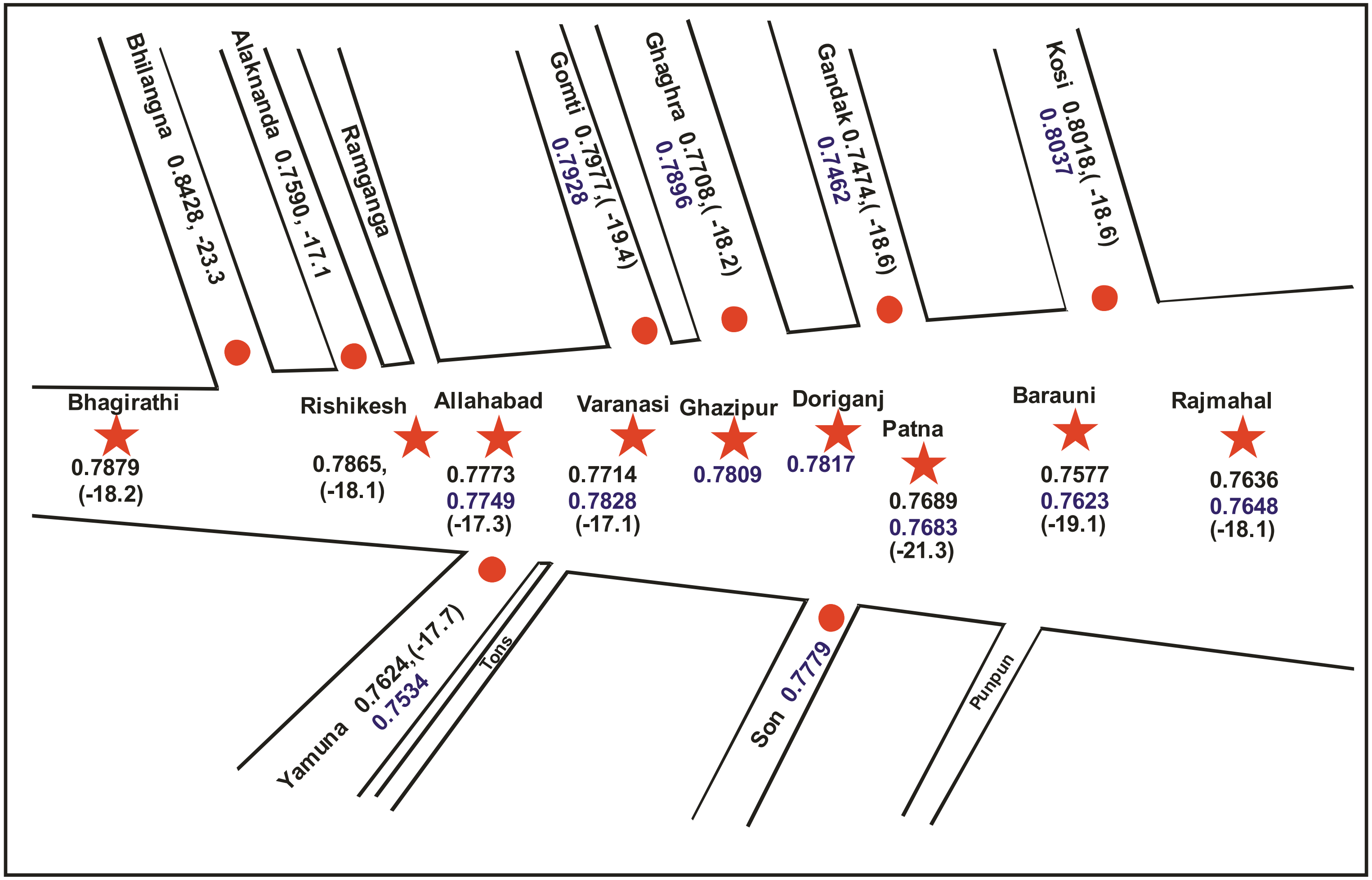


Fig-3.6: Funnel diagram (not to scale) of the Ganga mainstream and its tributaries along with $^{87}Sr/^{86}Sr$ for May 2003, 2004 and October, 2006 (values given in blue colour) and ε_{Nd} (May 2003, 2004; in parenthesis) in silicates of their bulk sediments. These data coupled with a two end member 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:

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

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

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

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

$$= 1 - f_{Gandak} \qquad \text{……………..} \; (3.3)$$

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).

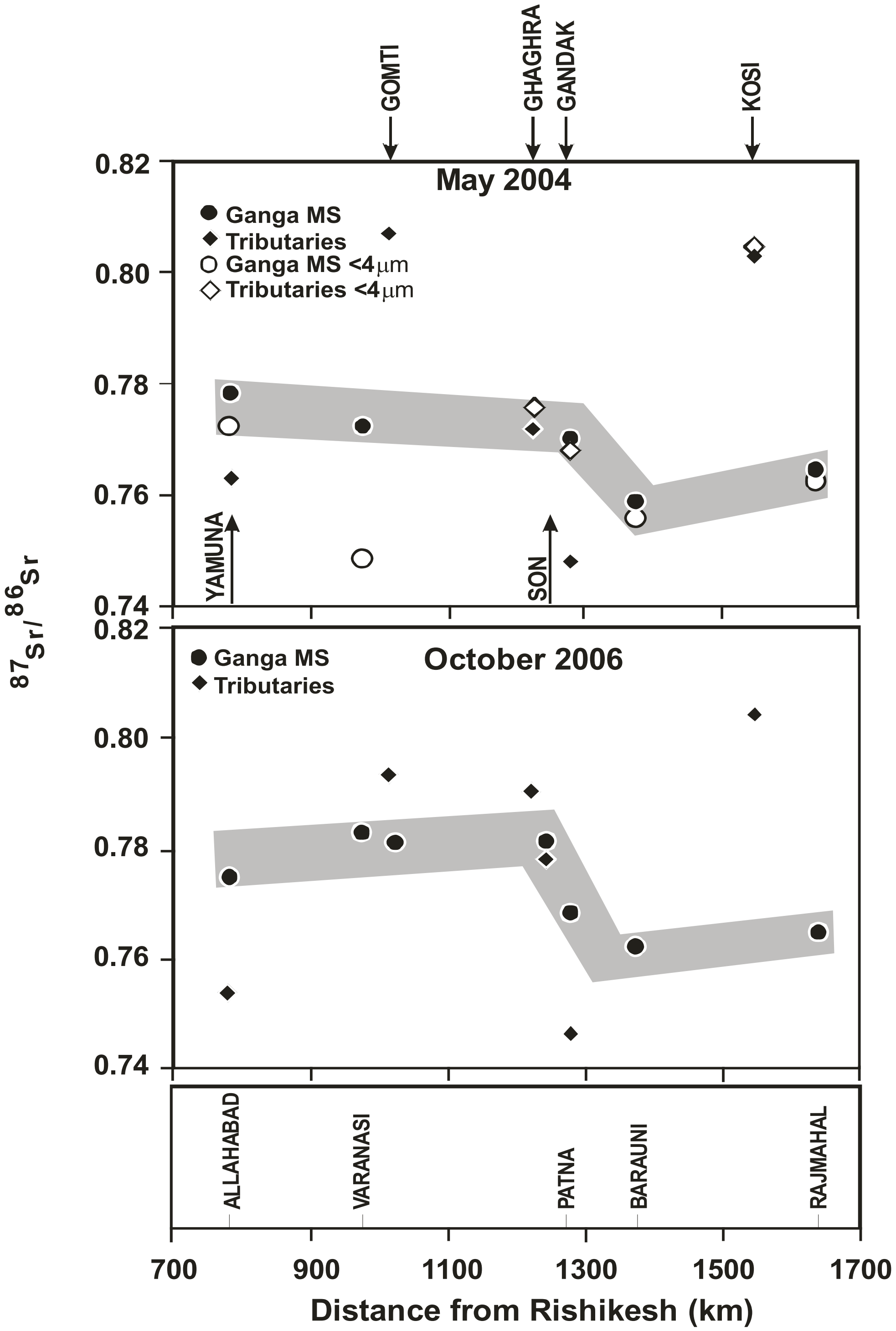


Fig-3.7; Downstream variations in $^{87}Sr/^{86}Sr$ values of silicates of the Ganga sediments during May 2004 and Oct 2006. During both the sampling periods, $^{87}Sr/^{86}Sr$ of the Ganga mainstream sediments decrease sharply at Barauni after the confluence with the Gandak and then increase marginally 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.

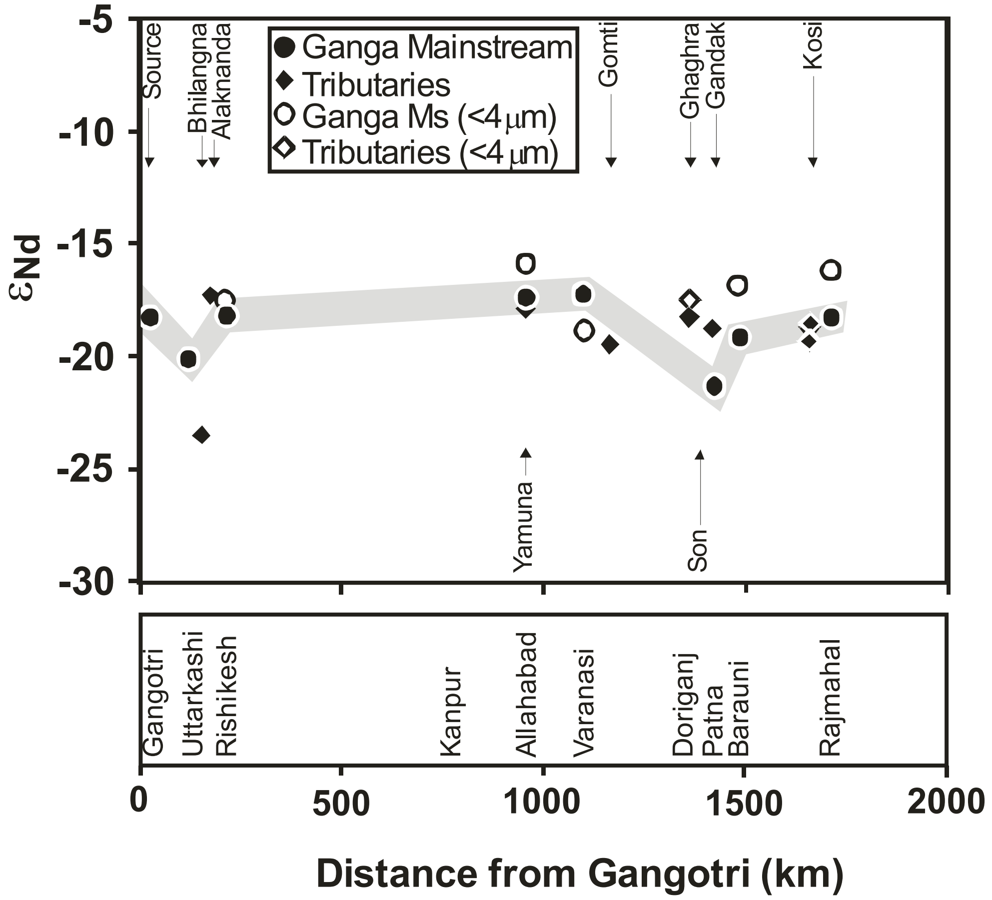


Fig-3.8: Downstream variation in ε_{Nd} of the Ganga mainstream sediments. Analogous to $^{87}Sr/^{86}Sr$, the downstream variations of ε_{Nd} is due to mixing of sediments from the Ganga mainstream with sediments of its tributaries.

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.

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

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 Fraction (%)		Sediment Yield tons km^{-2} yr^{-1}		Physical erosion rate (mm yr^{-1})			
	Himalayan	Total							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	100×10^6	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}.

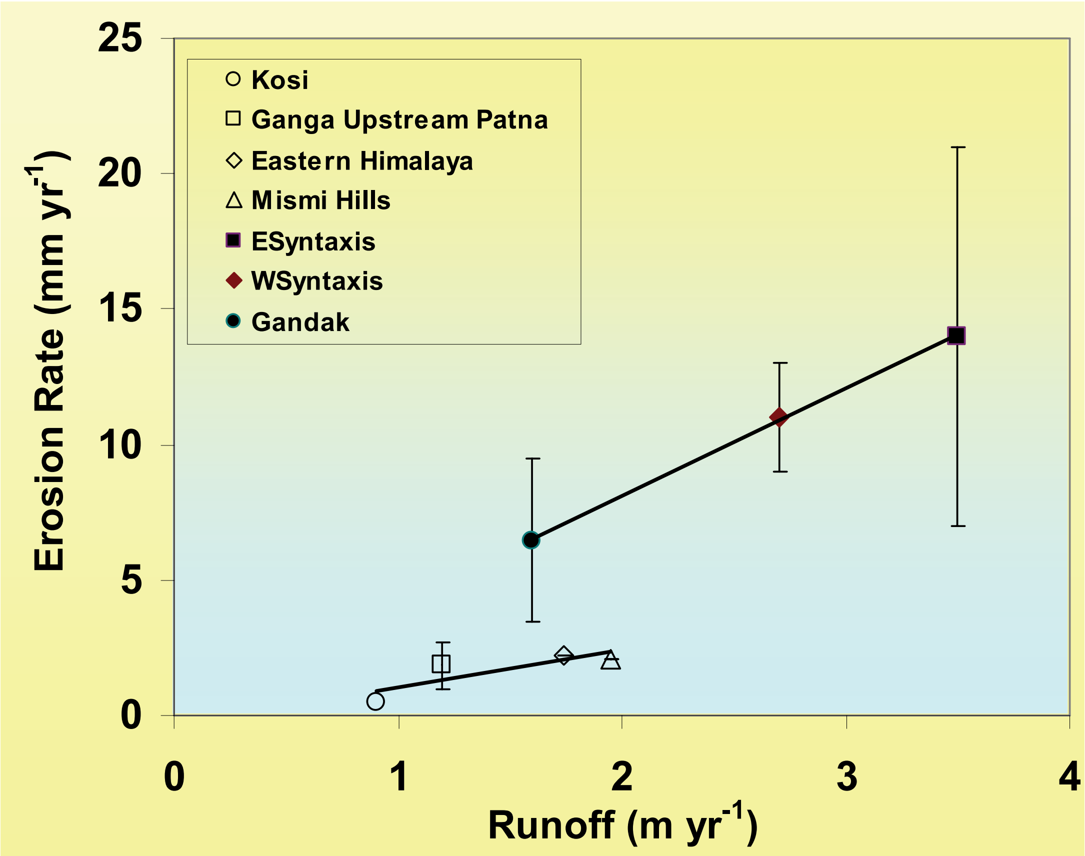


Fig-3.9: Physical erosion rates in the Ganga-Brahmaputra-Indus basins as a function of run off. Two trends are seen, one with gentler slope, for rivers with lower precipitation and lower relief and other for those with higher precipitation and higher relief. Data for the Kosi, Ganga (upstream of Patna) 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.

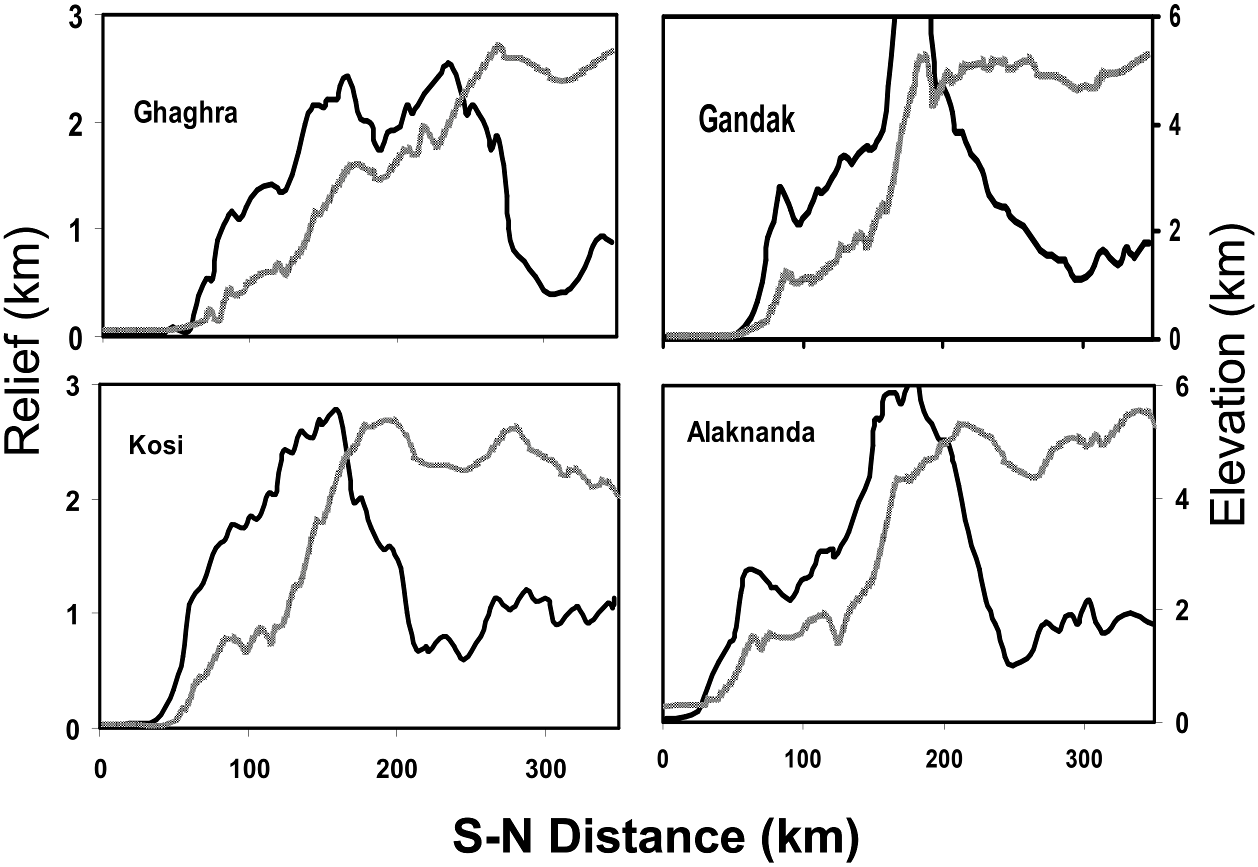


Fig-3.10: Elevation (grey line) and relief (black line) profiles of selected rivers of the Ganga basin (Bookhagen and Burbank, 2006). The relief of the Gandak drainage in the Higher Himalaya is higher than that of the others.

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.

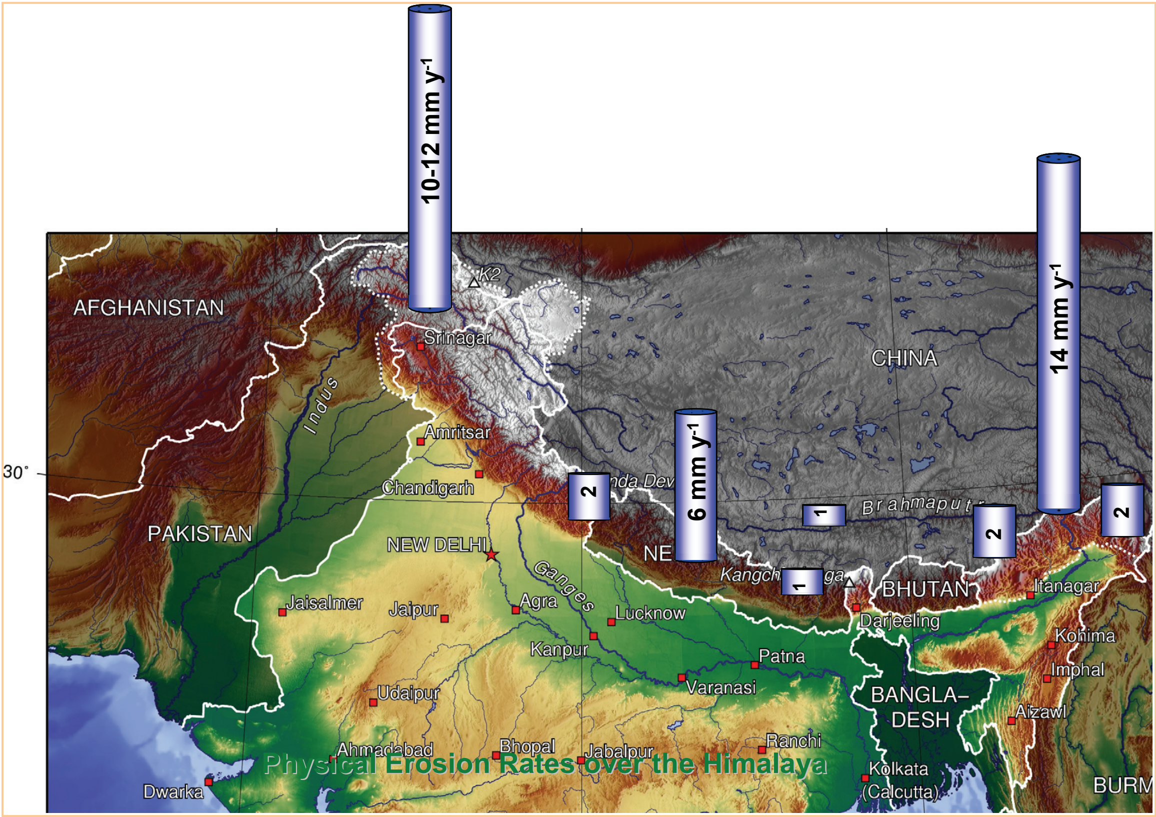


Fig-3.11: Locations of hotspots of physical erosion over the southern Himalaya. There are three hotspots, one each over the eastern and western syntaxes and third over the Gandak gorge. These hotspots control the sedimentary fluxes from the Himalaya and hence the sedimentary budget of the Bay of Bengal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

Chapter-4

Sr, $^{87}Sr/^{86}Sr$ and major ions in the Ganga River System: Chemical weathering in the Ganga plain and peninsular sub-basins and dissolved Ca and Sr budgets

4.1 Introduction:

This chapter presents results on the chemical and Sr isotope composition of water from the Ganga and its tributaries and their application to determine chemical weathering in plain, peninsular and Himalayan sub-basins of the Ganga and better understand Sr geochemistry in these rivers. The suggestion that silicate weathering in young organic belts such as the Himalaya is a key driver of climate change over million year time scales (Raymo and Ruddiman, 1992; Raymo et al., 1994; Ruddiman, 1997; Kump et al., 2000; Huh, 2003) led to a number of studies on the chemical and isotopic composition of the Ganga and the Brahmaputra (Sarin et al.,1989, 1992; Palmer and Edmond 1992; Krishnaswami et al.,1992, 1999; Edmond and Huh, 1997; Galy and France-Lanord, 1999; Dalai et al., 2002; Singh and France-Lanord, 2002; Bickle et al., 2003, 2005; Singh et al., 2005, 2006; Rai and Singh, 2007). Between these two rivers, the Ganga is relatively more investigated with many of the studies focusing on the Himalayan sub-basin of the Ganga drainage and a few others covering almost the entire stretch of the Ganga river system, from its origin in the Himalaya to its outflow to the Bay of Bengal (e.g. Sarin et al., 1989; Galy and France-Lanord, 1999; Krishnaswami et al., 1999). The latter studies yielded chemical and silicate erosion rates integrated over the entire Ganga basin spread over the Himalaya, the Ganga plain and the peninsular India. In spite of all these studies, there is only very limited information on the significance of chemical erosion in the plain and peninsular sub-basins of the Ganga, which account for ~80% of its drainage, in contributing to the flux of various elements transported by the Ganga to the Bay of Bengal. The available inferences (Galy and France-Lanord, 1999) seem to indicate that chemical erosion in the Ganga plain is much less than that in the Himalaya. One of the objectives of this thesis is to address this issue, i.e., to evaluate chemical erosion rates in the Ganga plain and peninsular sub-basins of the Ganga and their impact on its water chemistry and overall chemical erosion rate in the Ganga basin. Sr isotope studies of the G-B river system have been motivated by two major considerations (i) to assess the role of the G-B system and chemical weathering in the Himalaya in contributing to Sr isotope evolution of oceans since the Cenozoic (Krishnaswami et al., 1992, 1999; Raymo and Ruddiman, 1992; Richter et al., 1992; Ruddiman, 1997; Galy et al., 1999) and (ii) to explore the potential of Sr isotopes as a proxy of silicate weathering. It is known that the Sr isotope composition of the Ganga and the Brahmaputra are highly radiogenic compared to other global rivers (Fig-4.1; Palmer and Edmond, 1989; 1992; Krishnaswami et. al 1992, 1999; Edmond 1992; Galy et al., 1999; Singh et al., 1998, 2006; Bickle et al., 2003; Rai and Singh, 2007). It is suggested that the source of radiogenic Sr to these rivers is weathering of silicates of the Higher and Lesser Himalaya, which would make the Sr isotopic composition a good proxy for silicate weathering in their basins (Edmond 1992; Krishnaswami et. al., 1992, 1999; Raymo and Ruddiman, 1992; Singh et al., 1998; Krishnaswami and Singh, 1998; Galy et al., 1999; Bickle et al., 2003). This hypothesis, however, was questioned following the observations of highly radiogenic carbonates and vein calcites disseminated in the Himalaya (Palmer and Edmond., 1992; Harris et al., 1998; Jacobson and Blum, 2000; Bickle et al., 2003, 2005; Tipper et al., 2006). Recent studies of Bickle et al. (2005) based on detailed sampling of head waters of the Ganga and modeling concludes that the primary source of radiogenic Sr to these rivers is silicates. The application of Sr isotope as a proxy of silicate weathering is further hampered by difficulties associated with balancing the budget of Sr in rivers in terms of its supply from silicates and carbonates (Krishnaswami and Singh, 1998; Dalai et al., 2003). These attempts, based on Sr/Ca ratio and $^{87}Sr/^{86}Sr$ of the Ganga and Yamuna head waters, Pre-Cambrian carbonates and silicates observed that the Sr budget in these rivers could not be balanced if Ca in these waters behave conservatively. This led to suggest that in addition to carbonates and silicates there must be the other source(s) of Sr, low in both $^{87}Sr/^{86}Sr$ and Ca/Sr to account for its budget in these waters. A few other studies (Jacobson et al., 2002; Dalai et al., 2003; Bickle et al., 2005; Tipper et al., 2006), however, indicate that there could be removal of dissolved Ca via calcite precipitation and hence carbonate fraction of Sr derived from Ca abundance in river water could be an underestimate. Indeed, Jacobson et al. (2002) based on synthesis of available data on Sr, Ca/Sr, $^{87}Sr/^{86}Sr$ and modeling showed that precipitation of calcium carbonate in the Himalayan streams is an ongoing process and that about ~70% Ca in water can be lost due to calcite precipitation.

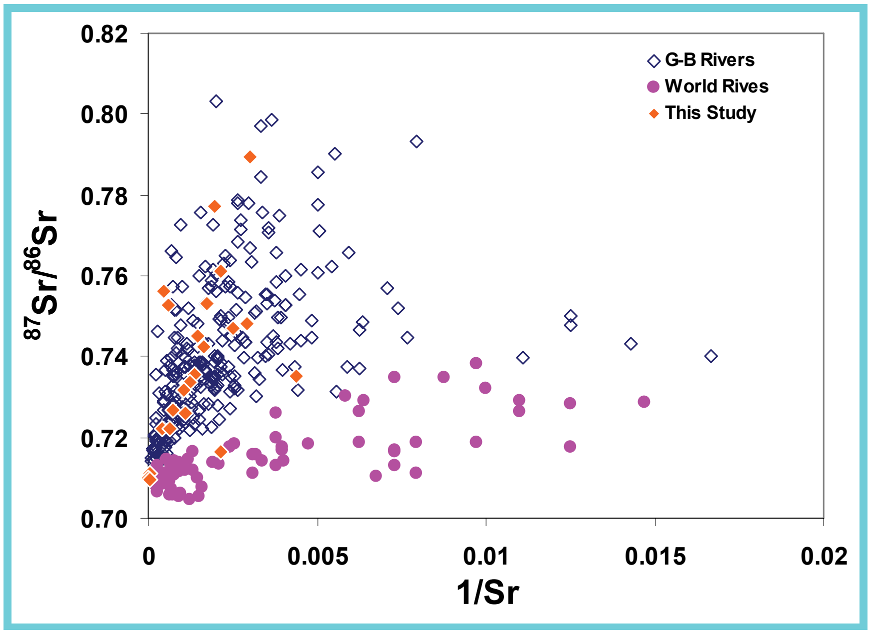


Fig-4.1: $^{87}Sr/^{86}Sr$ vs 1/Sr (Sr in ppb) plot of the G-B and global rivers. It is evident that in general the G-B rivers are more abundant in Sr with highly radiogenic $^{87}Sr/^{86}Sr$ relative to other global rivers.

Dalai et al. (2003) based on their studies of the Yamuna waters and sediments though hinted at the possibility that up to ~50% of Ca supplied to these waters could be lost by precipitation, they were uncertain if such removal is indeed occurring. Bickle et al. (2005) based on abundances of major ions, Sr and $^{87}Sr/^{86}Sr$ observed that ~50% of Sr in the Ganga headwaters is of silicate origin, the balance being contributed by carbonate weathering. More importantly, they concluded that the silicate sources provide ~ 70% of ^{87}Sr flux which regulates the seawater $^{87}Sr/^{86}Sr$ isotope composition.

In this work, a comprehensive study of major ions, Sr and $^{87}Sr/^{86}Sr$ have been carried out in water and sediments of the Ganga river collected from its entire stretch, from near its source at Gangotri to its mouth at Farakka and its tributaries. These measurements, as mentioned earlier have been carried out to determine chemical erosion in the Ganga plain and peninsular region and learn about Sr geochemistry in the Ganga system. Among the tributaries the Gomti, the Son and the Yamuna drain the plain and peninsular regions of the Ganga basin. The Gomti and the Son have their entire drainage in the Ganga plain and/or peninsular region (chapter-2; Fig-2.1). The Yamuna, though originates in the Himalaya, also has most of its drainage (~ 97 %) in the Ganga plain and peninsular region (Rao, 1975). The studies of these rivers therefore, can yield information on chemical erosion in the plain and peninsular regions of the Ganga basin and its comparison with erosion in Himalayan sub-basin of the Ganga. Further, the abundances of Mg-Ca-Sr in these rivers and their $^{87}Sr/^{86}Sr$ ratio along with those in a few other samples such as dripping and seepage waters from caves and fissures and precipitated carbonates have been used to learn more about the geochemistry of Ca-Sr in these waters, particularly calcite precipitation from them and its impact on dissolved Sr budget. The results of chemical erosion of the various sub-basins are presented first followed by Sr isotope and its investigations.

4.2 Results and Discussion:

The details of the river water sampling locations and the temperature and pH of the waters are presented in chapter-2 (Table-2.3). The results of major ions, silica, TDS, Sr and $^{87}Sr/^{86}Sr$ composition of the Ganga mainstream and its tributaries are given in Table-4.1. The results of analyses of seepage water, hot springs and other miscellaneous water samples are also presented in this Table-4.1.

4.2.1 General Observations:

Temperature of waters collected during the two summer field trips (May, 2003 and 2004) range from 17 to 34 °C. The range does not include the headwaters in the Himalaya as they were not measured. The pH shows a range of 7.3-8.6 suggestive of mild alkaline nature of the rivers sampled. The major ion data show good balance between total cations (TZ^+) and anions (TZ^-), the regression line through the data has a slope of 0.971±0.004 and $r^2 = 0.999$. Of the 50 samples analysed, 45 show normalized inorganic charge balance (NICB = $(TZ^{+}-TZ^{-})/TZ^{-}$) with an average deviation of 2.9±2.3%. This leads to conclude that the ions measured by and large account for the charge balance. Five samples however, have significant excess of anions ($TZ^{-} > TZ^{+}$ range 11- 23.3%). Analytical uncertainties associated with measurements is unlikely to be a cause for these considering the accuracy and precision of analyses as estimated from standards and repeats (presented in chapter-2, section 2.5.1) and the good charge balance observed for the other 45 samples. Therefore other reasons have to be invoked to explain this observation; one could be the presence of other cations in these waters, (e.g. $NH4^{+}$) which were not measured.

Total dissolved solids (TDS) show significant spatial and temporal variations along the course of the Ganga river (Fig-4.2). TDS for the May 2003 samples (head waters of the Ganga), vary from 49 to 153 mg ℓ^{-1}, lower than the values of 159 to 574 mg ℓ^{-1} in the Ganga and its tributaries in the plains (collected in summer 2004). For the October 2006 samples from the plains, TDS varies from 114 to 390 mg ℓ^{-1} showing the effect of dilution due to monsoon discharge. This effect is not prominent in case of the Gomti river (Fig-4.2). The lowest value of TDS (49 mg ℓ^{-1}) was measured in a small stream from the Higher Himalaya, (RW03-6). Water samples collected from a spring in the Higher Himalaya at Gang Nani (RW03-7) and those from the Shahashradhara and the Kempty fall in the Lesser Himalaya (RW03-19) show high TDS values 798 to 2422 mg ℓ^{-1} (Table-4.1). The discharge of such springs and seepage waters with high TDS into rivers can influence major ion budget of rivers in and around their confluence. The importance of spring water on the major and minor element budgets of the head waters of the Ganga system has been brought out in some of the earlier work (Evans et al., 2001; Bickle et al., 2003). The molar abundances of major cations in the Ganga headwaters decrease as Ca>Mg>Na>K (Table-4.1), consistent with that reported earlier (Sarin et al., 1989; 1992) in the region. Ca together with Mg account for ~85% of TZ^{+}, in upper reaches of the Ganga which decreases to ~75% for the Ganga mainstream and its tributaries in the plains.

Table-4.1: Dissolved major ions (μM), Sr (nM), TDS (mg/L) and $^{87}Sr/^{86}Sr$ in the Ganga river and its tributaries

Sample	River	Na	Na*	K	Mg	Ca	Cl	NO_3	F	SO_4	HCO_3	SiO_2	Sr	TDS	NICB $(TZ^+-TZ^-)/TZ^-$	$^{87}Sr/^{86}Sr$
Head Waters																
Bhagirathi system																
RW03-5	Bhagirathi (Gangotri)	90	78	43	86	245	12	0	39	353	188	127	468	69	-16.0	0.76101
RW03-8	Bhagirathi (Uttarkashi)	107	65	45	120	361	42	0	15	156	818	99	685	94	-6.2	0.74512
RW03-9	Syansu Gad	323	248	29	128	418	75	0	6	111	1261	240	1724	133	-7.6	0.75268
RW03-10	Bhilangana (Ghanshyali)	90	61	41	53	279	29	0	18	106	778	104	342	81	-23.3	0.74828
RW03-3	Bhagirathi (Devprayag)	130	97	42	137	347	33	0	21	184	811	121	571	98	-7.5	0.75330
RW03-6	Glacier melt (Higher Him.)	65	58	51	33	154	7	0	9	185	183	158	228	49	-14.0	0.73504
Alaknanda system																
RW03-4	Alaknanda (Devprayag)	91	71	40	165	403	20	0	10	150	1066	95	822	110	-9.2	0.73368
RW03-11	Alaknanda (Rudrapryayag)	79	56	43	166	460	23	0	9	145	1087	85	970	112	-2.5	0.73158
RW03-12	Mandakini (Rudrapryayag)	96	70	35	41	277	26	0	12	72	626	116	400	69	-5.0	0.74709
RW03-13	Birahi Ganga (Trib.)	27	18	40	166	340	9	0	3	52	1032	130	331	96	-6.0	0.78955
RW03-14	Birahi Ganga (Birahi)	121	90	62	321	541	31	0	25	145	1607	93	514	153	-2.3	0.77738
RW03-15	Alaknanda (Birahi bef. confl.)	95	74	36	190	451	21	0	11	218	978	87	1404	113	-2.2	0.72662
RW03-16	Pindar river (Pindar Valley)	58	39	41	168	481	19	0	9	96	1229	84	616	116	-3.6	0.74231
Ganga mainstream (2004)																
RW03-2	Ganga (Rishikesh, upstream)	106	77	41	164	419	29	0	13	175	973	107	731	108	-3.8	0.73572
BR-388	Ganga (Varanasi)	2380	1418	179	922	814	962	0	22	257	4631	321	3937	477	-1.6	0.71859
BR-309	Ganga (Patna)	1354	891	116	722	903	463	0	18	166	3986	275	3070	381	-1.6	0.72184
BR-318	Ganga (Rajmahal)	800	542	156	510	784	258	0	14	172	2865	197	2157	280	1.8	0.72673
Tributaries merging in Plain(2004)																
BR-346	Yamuna (Allahabad)	3575	2082	136	1104	794	1493	0	27	335	5300	325	5889	574	0.2	0.71467
BR-375	Gomti (Ghazipur)	1354	954	127	894	872	400	17	22	252	4193		3173	388	-2.4	0.72759
BR-342	Ghaghra (Revilganj)	446	374	102	569	762	72	0	13	163	2932	172	1952	266	-4.0	0.73125
BR-354	Ghaghra (Faizabad)	322	264	194	524	848	58	0	11	153	2944	176	1815	269	-1.8	0.73282
BR-363	Rapti (Gorakhpur)	565	450	166	703	950	115	0	13	136	3737	197	2157	331	-2.4	0.73009
BR-311	Gandak (Hazipur)	217	106	83	356	714	111	0	8	253	2182	146	3675	216	-13.1	0.73675

BR-334	Gandak (Barauli)	245	121	18	403	795	124	0	8	274	2211	157	1552	223	-8.0	0.73707
BR-327	Kosi (Dumarighat)	283	214	81	187	544	69	0	15	125	1578	174	742	157	-4.5	0.74806
<u>Ganga in Plain(2006)</u>																
BR06-12-1	Ganga (Allahabad)	829	529	164	528	685	300	24	7	238	2606	17	1655	261	0.2	0.72969
BR06-14-1	Ganga (Varanasi)	966	519	102	415	658	447	19	6	165	2424	61	2078	247	-0.3	0.71575
BR06-10-1	Ganga (Ghazipur)	876	456	94	367	632	420	15	6	156	2276	24	2033	229	-2.0	0.715532
BR06-801	Ganga (Doriganj)	422	294	79	369	800	128	9	5	132	2513	49	1530	228	-2.7	0.72447
BR06-301	Ganga (Patna)	495	332	75	376	725	164	9	6	124	2343	50	1561	217	0.1	0.72198
BR06-401	Ganga (Barauni)	407	277	78	364	754	131	8	5	137	2294	61	1447	213	0.3	0.72402
BR06-104	Ganga (Rajmahal)	334	240	75	273	709	94	4	5	96	2111	75	1122	192	-1.5	0.72707
<u>Tributaries merging in Plain (2006)</u>																
BR06-13-1	Yamuna (Allahabad)	1275	579	85	443	673	696	50	6	181	2572	129	2717	280	-2.6	0.71239
BR06-11-1	Gomti (Ghazipur)	1399	1075	130	848	859	324	7	10	200	4286	92	2717	390	-1.6	0.72714
BR06-901	Ghaghara (Revilganj)	256	212	74	384	867	43	11	4	131	2555	102	1373	230	-1.5	0.73002
BR06-705	Gandak (Hazipur)	138	99	82	308	712	39	11	3	187	1911	91	1064	184	-3.3	0.73526
BR06-201	Son (Koilawar)	431	315	43	253	537	116	11	8	50	1833	161	944	170	-0.6	0.72504
BR06-501	Kosi (Dhumarighat)	173	158	69	166	421	15	7	5	67	1252	114	467	118	0.2	0.75732
BR06-601	Bagmati (Dhumarighat)	224	176	70	155	542	48	8	5	51	1551	94	588	141	-1.5	0.74397
<u>Miscelanious water samples</u>																
RW03-20	Seepage water (Lokhandi)	77	47	13	429	1323	30	0	2	70	3513	151	1598	297	-2.5	0.72204
RW03-21	Seepage water (Lokhandi)	58	27	46	550	692	31	0	8	1228	413	135	913	196	-11.0	0.72615
RW03-22	Seepage water (Lokhandi)	17		6	1268	1104		0	4	534	3575	96	468	351	2.0	0.71626
MW03-1	Drip water	123	123	62	4379	5414						195	7454	339		0.71576
MW03-2	Drip water	26	26	15	2119	1815						152	1336	134		0.71517
MW03-3	Drip water	25	25	20	2026	1416						143	1236	115		0.71577
RW03-7	Gangnani (Hot spring)	10874	8688	547	312	1516	2186	30	382	368	11364	1603	2295	1248	2.6	0.75615
RW03-17	Drip water (S. Dhara)	62	35	38	2108	3687	27	0	97	3979	3348	145	16461	798	2.3	0.71093
RW03-18	Sulphurous water (S. Dhara)	339	297	61	4234	13773	42	0	66	15365	4420	203	84715	2422	3.3	0.70977
RW03-19	Stream water (Kempty Fall)	76	40	28	2979	4304	36	0	41	5734	2844	159	28607	982	1.9	0.70950
RW03-1	Bandal (sherki)	91	91	43	918	1009					2883	141	2443			0.72209

It is evident from the ternary plot (Fig-4.3a) that many of the river water samples analysed are closer to the Ca apex with some of the Ganga mainstream and tributaries in the plain heading towards (Na+K) apex. The drip, seepage and fall water samples fall along the Ca-Mg mixing line, the exception being the Gangnani sample which is dominated by Na (Table-4.1).

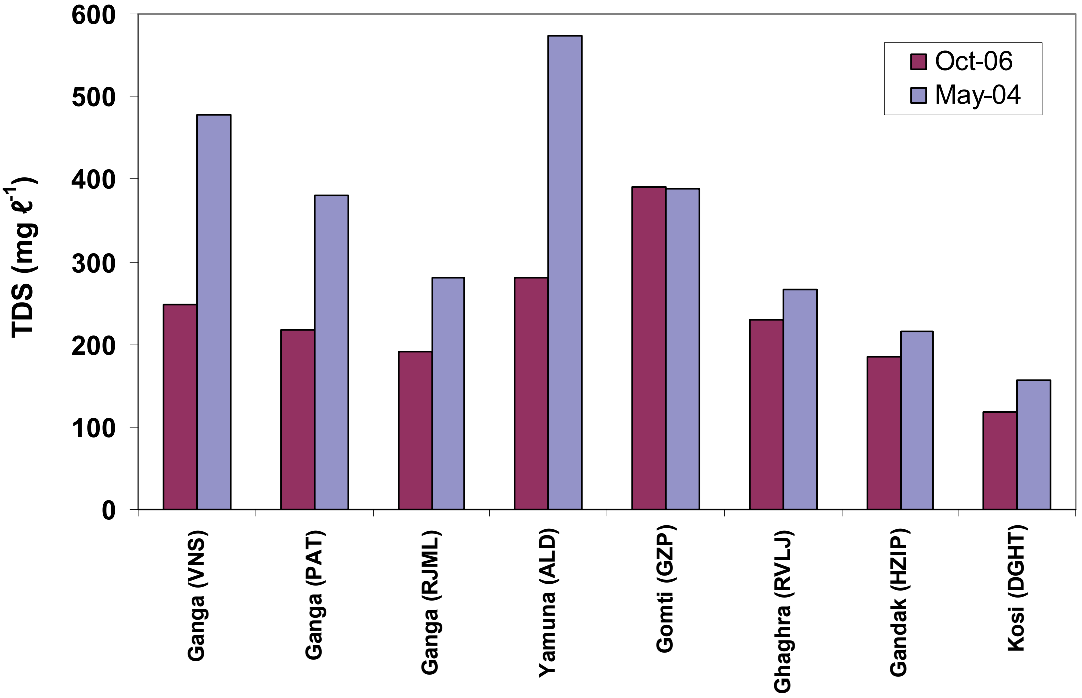
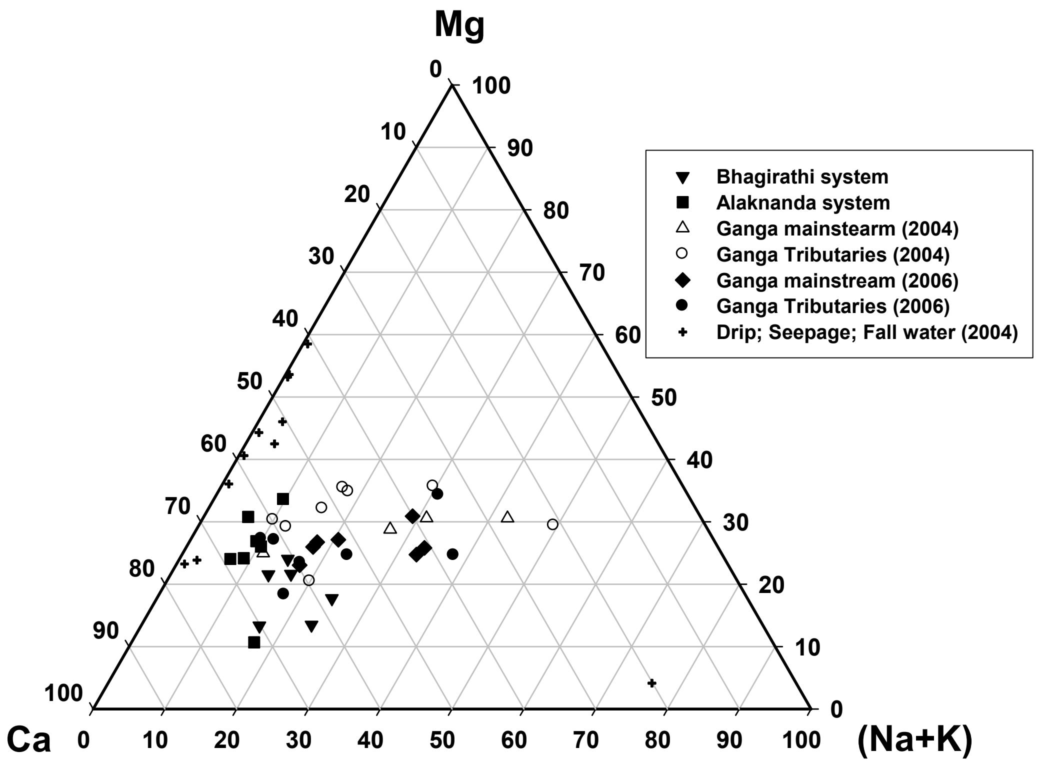
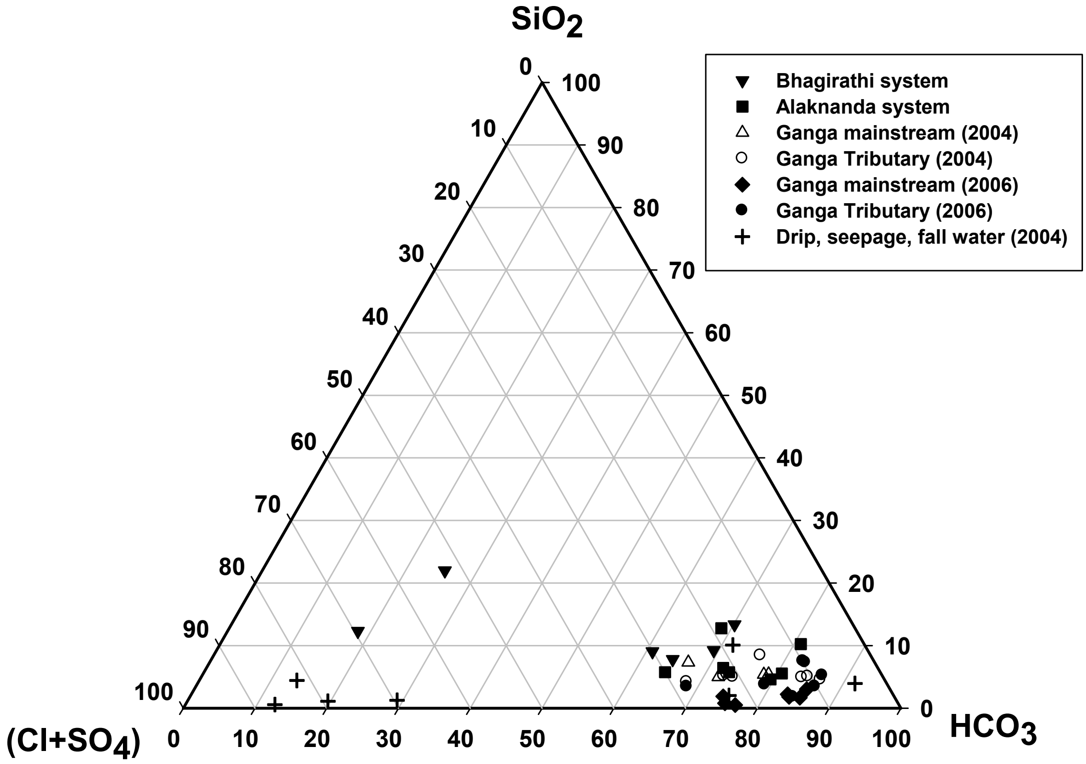


Fig-4.2: Variation in TDS of the Ganga river and its tributaries during two sampling periods, May 2004 and October 2006.

Ca and Mg can be derived from silicates, carbonates and evaporites (gypsum) and minor phases such as apatite. The apportionment of contributions from these various sources is important to estimate silicate and carbonate erosion in the basin and their impact on the draw-down of atmospheric CO_2. Fig-4.4 is a comparison of Ca, Mg and Na abundances along the course of the Ganga mainstream with those reported by Sarin et al. (1989) at the same locations for samples collected in March 1982. It is seen from the figure that the abundances of all these elements are higher in May 2004 compared to March 1982 samples. This difference can be a result of multiple factors such as reduced water flow in May compared to March, enhanced ground water input, interannual variation in major ion abundances or a combination of these.



(a) Ternary plot of cations (μE)



(b)Ternary plot of anions (μE)

Fig-4.3a &b: Ternary plots of major cations (a) and anions (b) in the Ganga head waters, mainstream and tributaries measured during different field campaigns. The data of miscellaneous water samples are also plotted (Table-4.1).

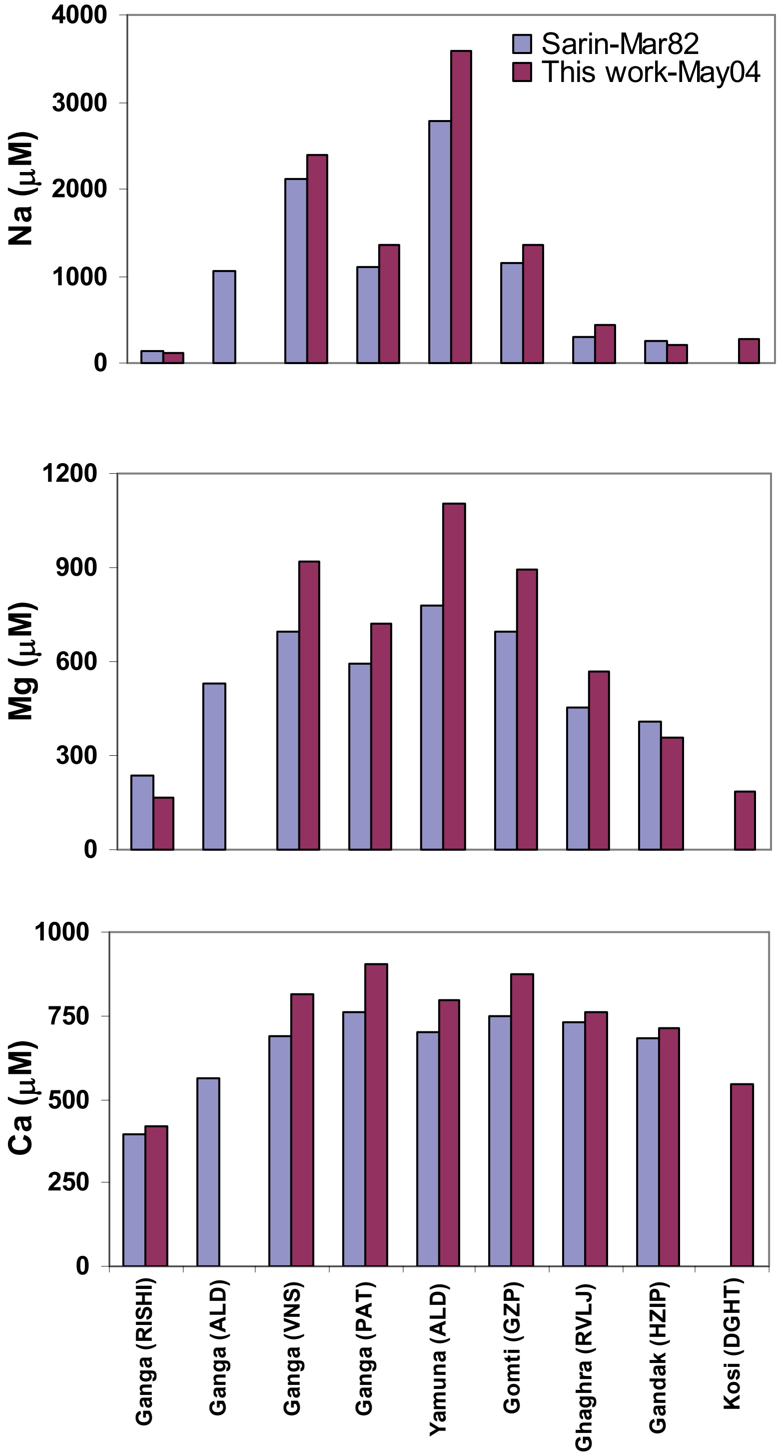


Fig-4.4: Comparison of Ca, Mg and Na abundances in the Ganga mainstream measured in this study with those reported for the sample collected during 1982/83 from the same locations by Sarin et al., (1989). The codes in parentheses refer to sample locations. RISHI= Rishikesh; ALD=Allahabad; VNS=Varanasi; PAT= Patna; GZP= Ghazipur; RVLJ= Revilganj; HZIP= Hazipur; DGHT= Dumarighat.

Among anions, HCO_3 is generally the most abundant, contributing ~ 70 % of TZ^- in the source region and ~80% in the plains (Fig-4.3b). The anion abundances decrease as $HCO_3 > SO_4 > Cl > F > NO_3$ in the headwaters. In the anion ternary plot (Fig-4.3b), the spring, seepage and Kempty Fall samples tend towards the $(Cl+SO_4)$ apex in contrast to the river samples which cluster around the HCO_3 apex. This observation brings out the importance of evaporites (gypsum and halite) and sulfuric acid weathering in regulating the major ion composition of these spring, seepage and water fall samples. Among the river waters, two samples from the upper reaches of the Bhagirathi plot away from the HCO_3 apex (Fig-4.3b). These two samples (RW03-5 & RW03-6) have high SO_4 and $SO_4/Ca > 1$ indicating the supply of SO_4 by pyrite oxidation. Sarin et al. (1992) also observed $SO_4/Ca > 1$ in the Bhagirathi sample from the Gangotri. Fig-4.5 is a plot of (Ca+Mg) vs (HCO_3+SO_4) in the water samples. The plot shows that the data of the Bhagirathi, Alaknanda and other samples collected during Oct 2006 all lie close to, but above the equiline. In contrast, the data of samples collected during summer of 2004 from the Ganga plain lie far away from the equiline, showing definite excess of (HCO_3+SO_4). This trend, as discussed later is a result of contribution of Na salts from alkaline/saline soils.

There is no detectable NO_3 throughout the Ganga in summer, however the monsoon samples from the plain show an average NO_3 concentration of 14 μM, with a range between 4 and 50 μM (Table-4.1). The highest NO_3 concentration is found in the Yamuna (50 μM) whereas in the mainstream Ganga the Allahabad sample, before the confluence of the Yamuna, has the highest concentration, 24 μM. The source of NO_3 can be atmospheric deposition and/or of industrial waste from units near Allahabad or from fertilizers used in agricultural fields of this region. The presence of measurable NO_3 brings out the role anthropogenic sources may have on the supply of nutrients to the Ganga river. Fluoride concentration along the entire stretch of the Ganga, from Gangotri to Rajmahal, in summer ranges from 3 to 39 μM with an average of 15 μM (May 2003, 2004). This value decreases to ~6 μM in samples from the plain collected during October 2006 attributable to dilution by rains. Fluoride can be introduced in rivers from precipitation (Madhavan and Subramanian, 2001) and through weathering of fluorite and/or fluor-apatite, the latter is known to be disseminated in the Himalaya (Jain et al., 2000; Catlos et al., 2007).

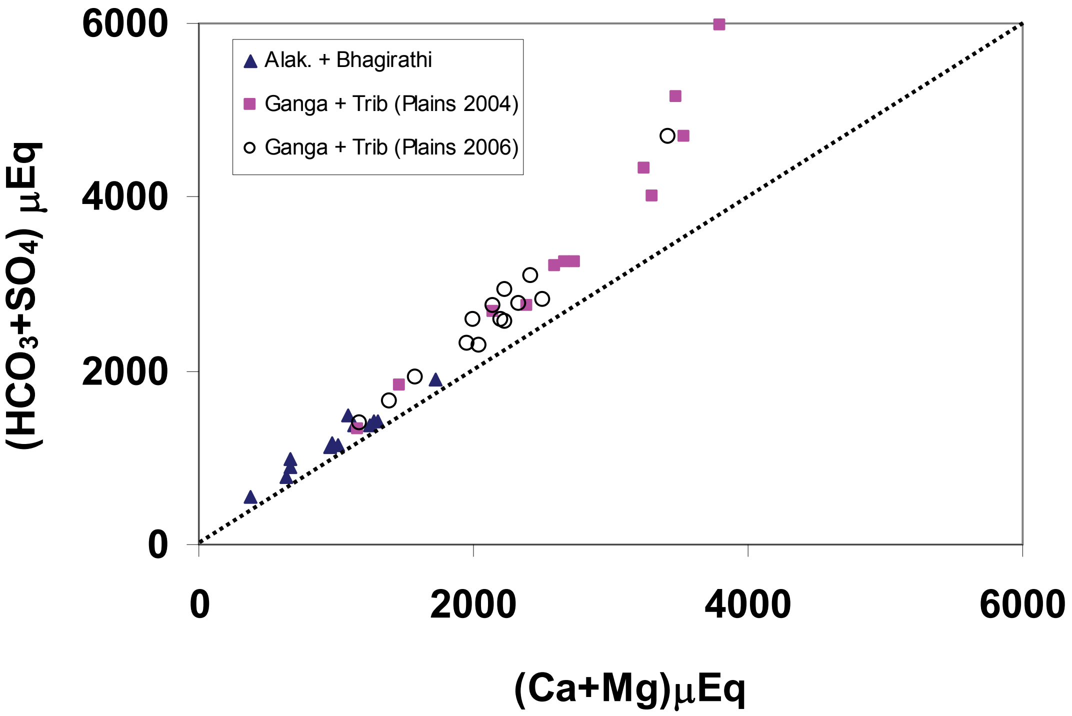


Fig-4.5: Scatter plot of (Ca+Mg) and (Alkalinity + SO_4). The dashed line represents 1:1 ratio. Deviation from the equiline, particularly in samples collected during May 2004 indicates the contribution of (HCO_3+SO_4) as Na salts from alkaline/saline soils in the Ganga plain.

Dissolved Si in the Ganga headwaters (Bhagirathi and Alaknanda) has a range of 84 µM to 240 µM (Table-4.1) with an average of ~120 µM. Si concentrations in the Ganga main stream in plain show significant variation between May 2004 and October 2006, with the later samples having much lower values (Table-4.1). Among the samples analysed highest Si concentration (325 µM) was observed in the Yamuna sample at Allahabad during May 2004. The high Si abundance in Yamuna water can result from weathering of Deccan Basalts. Rengarajan et al. (2008) in their study of the Chambal, the major tributary of the Yamuna, draining the Deccan basalts reported high Si, with values ranging from 157 to 607 µM. Si/(Na*+K) molar ratio has been used as a proxy to investigate intensity of silicate weathering in river basins (Stallard, 1980; Stallard and Edmond, 1983; Sarin et al.,1989). The ratio is ~1.0 to 1.4 in the Ganga head waters, and drops to quite low values in the plain. This drop is a result of Na addition to water thereby rendering Si/(Na*+K) ratio a less reliable proxy to learn about silicate weathering (see later discussion).

4.2.2 Water Chemistry of the Gomti, Yamuna and the Son and its impact on the chemistry of the Ganga Mainstream in the plain

The chemistry of the rivers draining these three regions is discussed together as they are used to derive chemical erosion in the plain and peninsular sub-basins of the Ganga drainage. The major ion chemistry of the Gomti waters sampled during both May and October is nearly the same (Table-4.2) with high abundances of Na, Mg and Ca and highest TDS among all the October samples (Table-4.1). The major ion composition of the Gomti measured in this study is very similar to that reported by Sarin et al. (1989) in samples of March and November 1982/83, from Dhobni, a few kms upstream of Ghazipur. The moderately high concentrations of Mg (~870 ± 25 μM) and Ca (~860 ± 10 μM) in samples (Table-4.2) suggest that carbonate weathering is prevalent in the Gomti basin. Further, the similar or higher concentrations of Mg and Ca in the Gomti, relative to that in the Ghaghra and the Gandak, the Himalayan tributaries of the Ganga (Table-4.1), suggest that the role of carbonates in contributing to the major ion chemistry of all these three rivers is roughly similar. Some of the earlier work (Singh et al., 2005b) on particulate and dissolved phases of the Gomti has hinted at the possibility of precipitated carbonates (kankar) as a potential source of Ca to the Gomti river. The Sr isotope composition of the Gomti water and sediment also attests to the dominant role of carbonates in determining its water chemistry. The ^{87}Sr/^{86}Sr of the Gomti water, 0.7271 – 0.7276 (Table-4.2) is far less radiogenic compared to the ^{87}Sr/^{86}Sr of silicate fraction of its bed sediments (0.79276, Table-3.1 chapter-3, Singh et al., 2008). The lower ^{87}Sr/^{86}Sr of water relative to bed sediment silicates, most likely results from mixing of Sr derived from radiogenic silicates and unradiogenic carbonates.

The chemistry of the Yamuna waters (Allahabad) is unique with the May sample having the highest TDS, Na, Mg, Cl and Sr among the samples analyzed (Table-4.2). The cations (equivalent units) in this sample decrease as Na > Mg > Ca > K, unlike the Himalayan tributaries which generally have Ca > Mg > Na > K (Table-4.1). The data of Sarin et al., (1989) also show high Na in the Yamuna at Allahabad during both March/ November 1982-83. Na abundance in both the Gomti and Yamuna (Allahabad) rivers are quite high among the rivers of the Ganga system and range between 1275 to 3575 µM (Table-4.2). In general, Na^+ is a significant contributor to cation charge in samples with TZ^+ >3000 µEq. There is a significant excess of Na over Cl in these samples (Tables-4.1, 4.2) suggesting that sources in addition to halite dissolution supply Na to them. Charge balance considerations show that in some of these samples, $Na^+ > (Cl^- + 2SO_4^{2-})$ requiring part of Na^+ in them to be associated with HCO_3^-.

Table-4.2 Major ions (µM), TDS (mg ℓ^{-1}), Sr (nM) and $^{87}Sr/^{86}Sr$ in the Gomti, Son and the Yamuna Rivers

River (Location)	Na	K	Mg	Ca	Cl	NO_3	SO_4	HCO_3	SiO_2	TDS	Sr	$^{87}Sr/^{86}Sr$
Gomti (Ghazipur)												
May-04	1354	127	894	872	400	17	252	4193	-	388	3173	0.72759
Oct-06	1399	130	848	859	324	7	200	4286	92	390	2717	0.72714
Son (Koilawar)												
Oct-06	431	43	253	537	116	11	50	1833	161	170	944	0.72504
Yamuna (Batamandi)*												
Jun-99	306	49	661	967	73	6	556	2508	193	285	2044	-
Oct-98	255	52	497	1019	60	35	333	2369	211	254	1802	0.72356
Yamuna (Allahabad)												
May-04	3575	136	1104	794	1493	0	335	5300	325	574	5889	0.71467
Oct-06	1275	85	443	673	696	50	181	2575	129	280	2717	0.71239

* at foot-hills of the Himalaya. Data from Dalai et al., (2002)

Silicate weathering in the basin by carbonic acid can contribute to this association. Alternatively, in the Yamuna, Gomti and the Ganga (samples downstream of Allahabad), saline and alkaline soils occurring in their basins

(Agarwal and Gupta, 1968; Bhargava and Bhattacharjee 1982; Sarin et al.,1989; Datta et al.,2002; Singh et al.,2004; Singh et al.,2005b) can supply Na as Na_2SO_4, $NaHCO_3$ and Na_2CO_3. These soils lie in the semi-arid alluvial regions of Uttar Pradesh, (south west Ganga basin) parts of Haryana and Bihar. In Uttar Pradesh, the salt affected zone occurs between the intervluves of Ganga-Yamuna and Ganga-Ghaghra rivers (Fig-4.6). Saline/alkaline soils are frequent in patches (Agrawal and Gupta 1968) in low lying areas of the state where water logging conditions prevail.

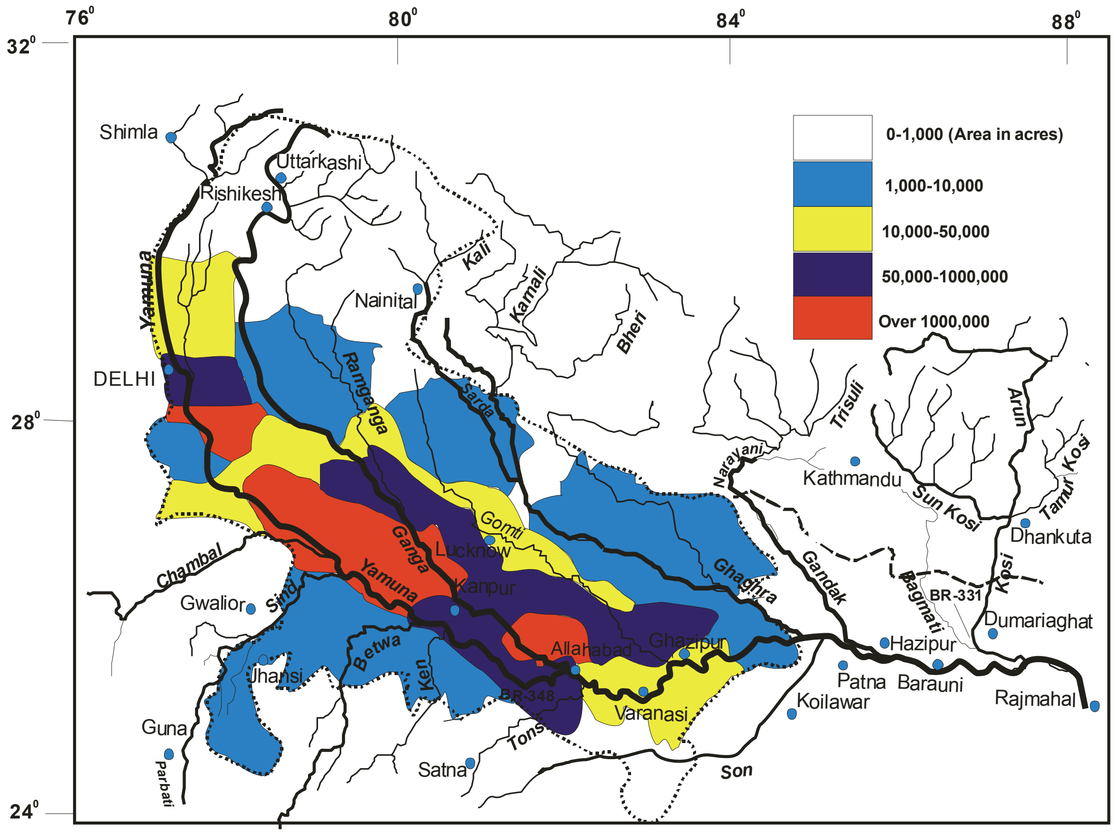


Fig-4.6: Arial distribution of salt affected (usar) soils in different parts of Uttar Pradesh (after Agarwal and Gupta, 1968)

Table-4.3: Chemical composition of water extract of salt affected surface soils from the Ganga plain (mE: milli equivalents)

Location	Ca	Mg	K	Na	CO_3	HCO_3	Cl	SO_4
Kasimabad (Hardoi, UP)	3.5	1.0	1.5	145.0	90.0	51.0	8.0	0.0
Malihabad (Lucknow, UP)	8.0	3.0	0.8	155.9	142.0	13.0	14.0	0.0
Kasimabad (Hardoi, UP)	2.0	0.5		27.1	0.0	18.0	10.0	0.0
Ghatampur (Kanpur, UP)	3.5	3.0	0.3	10.1	0.0	6.0	11.0	0.0
Shikarpur (Azamgarh, UP)	1.6	1.0		4.6		1.2		
Gaura (Azamgarh, UP)	1.0	-	-	115.6	2.8	9.0	1.8	111.6

Source: Agarwal and Gupta (1968) and references therein

Table-4.4: Salt Composition of surface soils from the Ganga plains

Location	Total soluble Salt (%)	Na_2CO_3 (%)	$NaHCO_3$ (%)	NaCl (%)	Na_2SO_4 (%)
Saline Soils					
Ghazipur (UP)	4.690			1.500	2.790
Western Yamuna Canal (UP)	3.087	0.904	-	1.142	1.093
Barauli (Farrukhbad,UP)	1.494	0.087	-	0.116	1.318
Chinhat (Lucknow, UP)	0.261	0.197	-	0.048	0.046
Cherat (Agra, UP)	0.095	0.813	-	0.071	0.063
Ganga Khadir (Aligarh, UP)	0.200	0.007	0.131	0.021	0.014
Ganga Khadir (Meerut, UP)	0.303	-	0.249	0.015	
Yamuna Khadir (Aligarh, UP)	0.710	-	0.083	0.156	0.484
Saline -Alkali Soil					
Bicjpuri , Etah (UP)		0.030	0.042	0.007	-
Bicjpuri , Etah (UP)		0.065	0.057	0.014	-

Source: Agarwal and Gupta (1968) and references therein

In the central part of the Indo-Gangetic plain, these soils are called *Usar (meaning sterile or barren) or Reh* with hard surface devoid of vegetation and are characterized by white/grayish white or ash coloured salt encrustations during dry periods. The surfaces of these soils are quite impermeable causing poor or impeded drainage resulting in water stagnation. Analyses of these soils for their Na salts and water soluble extracts are available (Tables-4.3, 4.4) which shows considerable variation. This constrains the estimation of their contribution to the solute budget of the Ganga, particularly Na, SO_4 and alkalinity downstream of Allahabad. *Kankar* (impure calcium carbonate nodule) frequently occur at depths in these soils (Kumar et al., 1996).

The role of these soils on the Na budget of the Son, Yamuna, Gomti and the Ganga downstream Allahabad is also evident from the SiO_2/Na^{**} ratios in them (Na^{**} is Na corrected for both rain and evaporite input, $Na^{**} = Na_r - Cl_r$) During May 2003, the (SiO_2/Na^{**}) in the Ganga headwaters is ~1.4 (Table-4.1), similar to the values reported by Sarin et al. (1989). This value decreases to ≤ 0.4 and ≤ 0.3 in the Ganga downstream of Allahabad during May 2004 and October 2006 respectively. The (SiO_2/Na^{**}) is lowest, ≤ 0.2, in the Gomti and the Yamuna (Allahabad). Such low (SiO_2/Na^{**}) ratios, ≤ 0.4, is difficult to be explained in terms of weathering of common silicate minerals

(Stallard, 1995; Drever, 2002), making it necessary to invoke supply of Na from sources in addition to silicate weathering to interpret the data. Sodium salts contained in alkaline and saline soils of the drainage basins is very likely to be this additional source. Such a source can add Na to water with little (or no) SiO_2 and thus bring down the SiO_2/Na** in water. Further, the supply of such non-chloride Na salts from the alkaline/saline soils can contribute to errors in the estimation of silicate derived Na in water and thus constrain the use of Na** as a proxy to determine silicate weathering rates in these river basins. The silicate erosion rates and associated CO_2 consumption rates of the Ganga basin calculated based on Na** in the Ganga waters downstream Allahabad in some of the earlier studies (e.g. Krishnswami et al.,1999; Galy and France-Lanord, 1999) can be an overestimate if part of Na** is derived from alkaline/saline soils (Rengarajan et al., 2008).

The high Ca and Mg concentration in the Yamuna are attributable to weathering of plagioclase and mafic minerals of Deccan basalts (Das et al., 2005) and carbonates of the Vindhyan in the basins of its peninsular tributaries. Indeed, the studies of Rengarajan et al. (2008) on the Chambal, the major tributary of the Yamuna, draining the Deccan Traps and Vindhyan show high Mg and Ca abundances even in samples collected during monsoon.

The abundances of major ions, except Ca, in the Yamuna decrease by factors of ~ 2 to 3 in the October samples due to dilution by monsoon discharge. Ca abundance in the Yamuna and the Ganga mainstream shows marginal decrease (~10% - 20%) in the October samples relative to summer samples from the same locations. The trends in Ca, Mg and Na variation along the Ganga mainstream in October is roughly similar to that observed during summer of 2004, except as mentioned above, their concentrations are lower in the October samples due to dilution by south-west monsoon rains.

In comparison to both the Yamuna and the Gomti, the abundances of Ca, Mg and Na in the Son are generally lower (Table-4.2). This can result from a number of factors that include higher rainfall and runoff in its drainage, lesser exposure of carbonates and the less weatherability of the Archean granites and sand stones of the Gondwana and the Vindhyan in the Son basin. The drainage of the Son in the Ganga plain also contains alkaline/saline soils (Singh et al., 2004) which can contribute to the Na budget of the Son river.

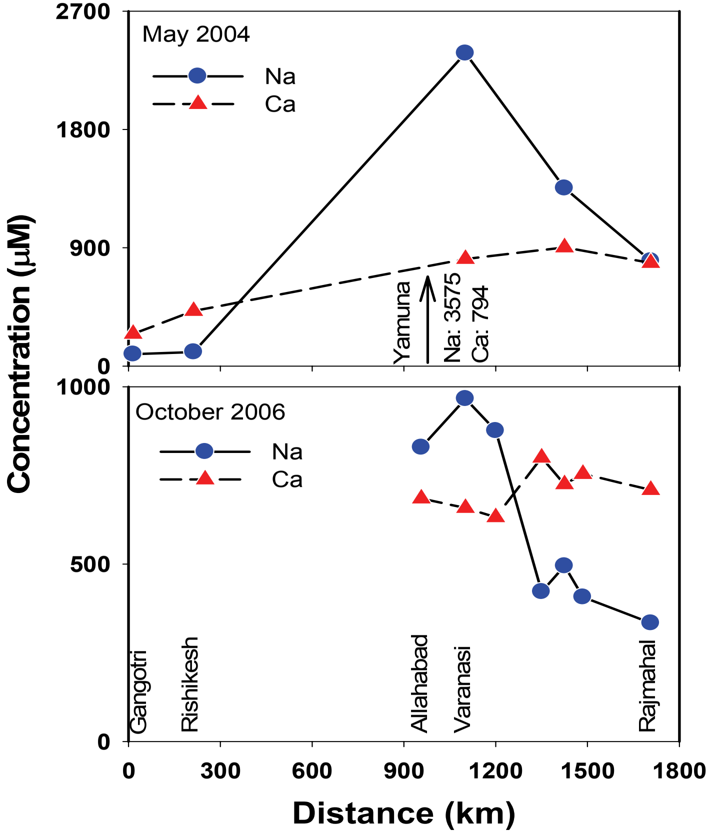
The impact of mixing of the Yamuna waters with the Ganga is clearly evident from the sharp increase in the concentration of Na and to a lesser extent in Mg, Ca and TDS in the Ganga waters at Allahabad / Varanasi (Table-4.1, Fig-4.7) during May. In October, such trends could not be looked for as the sampling was done only downstream of Allahabad. The data, however, show that among the samples analysed Na is highest in Varanasi (Fig.4.7). In the May samples, maximum increase is for Na, from 106 μM at Rishikesh to 2380 μM at Varanasi (Table-4.1, Fig-4.7). Fig-4.8 is a plot of Na vs Cl for the May and October samples of the Ganga mainstream in the plain. Also included in the plot are data for the Ganga at Rishikesh (or the Ghaghra at Revilganj) and the Yamuna at Allahabad. It is seen from the plot that during both the seasons the data show a strong linear trend, attributable to two component mixing, the low Na and Cl Himalayan end member (Rishikesh/Ghaghra) with the high Na and Cl Yamuna at Allahabad. This trend demonstrates the important role of Yamuna waters in determining the Na abundance of the Ganga downstream of its confluence. The best fit lines for the data in Fig-4.8 show that they plot well above the halite line, due to Na excess over chloride. The high Na in the Yamuna, as mentioned earlier, is dominated by contribution from alkaline/saline soils.

During the same period, Ca also increases from 419 μM at Rishikesh to 814 μM at Varanasi whereas the change in Mg is from 164 to 922 μm, double that of Ca. This increase, analogous to that of Na, is a result of mixing of Ca and Mg rich Yamuna (Table-4.1) with the Ganga and due to chemical weathering in the plain between Rishikesh and Varanasi. Downstream of Varanasi, Ca in the Ganga varies within a narrow range of 784 to 903 μM, similar to those of its tributaries, the Ghaghra and the Gandak, ~750 μM (Table-4.5). The concentration of Ca in the October samples, in both the Ganga mainstream and the Ghaghra and the Gandak are marginally lower relative to the May value. The near uniform abundance of Ca in the Ganga and its tributaries from the Himalaya, plain and peninsular India is intriguing and may be a influenced by calcite saturation. Indeed, calcite saturation index (CSI) calculated for the mainstream and tributary waters for the 2004 samples shows that all samples (except Kosi waters at Dumarighat and the Alaknanda in its upper reaches) are supersaturated in calcite and hence are prone to removal of Ca from the dissolved phase via its precipitation.

Table-4.5: Ca, Mg abundance and Ca/Mg in the Ganga system

Location		**Distance** (**From Rishikesh)**	**Ca**	**Mg**	**Ca/Mg**
Ganga Mainstream					
RISHI	2004	0	419	164	2.55
	2006				
ALD	2004	782			
	2006		685	528	1.30
VNS	2004	974	814	922	0.88
	2006		658	415	1.59
PAT	2004	1280	903	722	1.25
	2006		725	376	1.93
BRNI	2004	1375			
	2006		754	364	2.07
RJML	2004	1640	784	510	1.54
	2006		709	273	2.59
Ganga Tributaries					
YAMUNA	2004	784	794	1104	0.72
(Allahabad)	2006		673	443	1.52
GOMTI	2004	1016	872	894	0.98
(Ghazipur)	2006		859	848	1.01
GHAGHRA	2004	1224	762	569	1.34
(Revilganj)	2006		867	384	2.26
GANDAK	2004	1281	714	356	2.01
(Hazipur)	2006		712	308	2.31
KOSI	2004	1550	544	187	2.91
(Dumarighat)	2006		421	166	2.53

Further evidence of Ca removal comes from the relations of Ca/Mg with Ca and CSI (Figs-4.9 and 4.10).These scatter diagrams show that Ca/Mg decreases with increase in both Ca and CSI. This can be explained in terms of preferential loss of Ca during precipitation of $CaCO_3$. From Varanasi to Rajmahal, Mg decreases from 922 to 510 µM (Table-4.5), primarily because of mixing with relatively Mg poor waters of the Ghaghra, Gandak and the Kosi. Among these three Himalayan tributaries the Kosi has the lowest Ca and Mg consistent with low aerial coverage of the Lesser Himalayan carbonates in its basin (Quade et al., 2003).



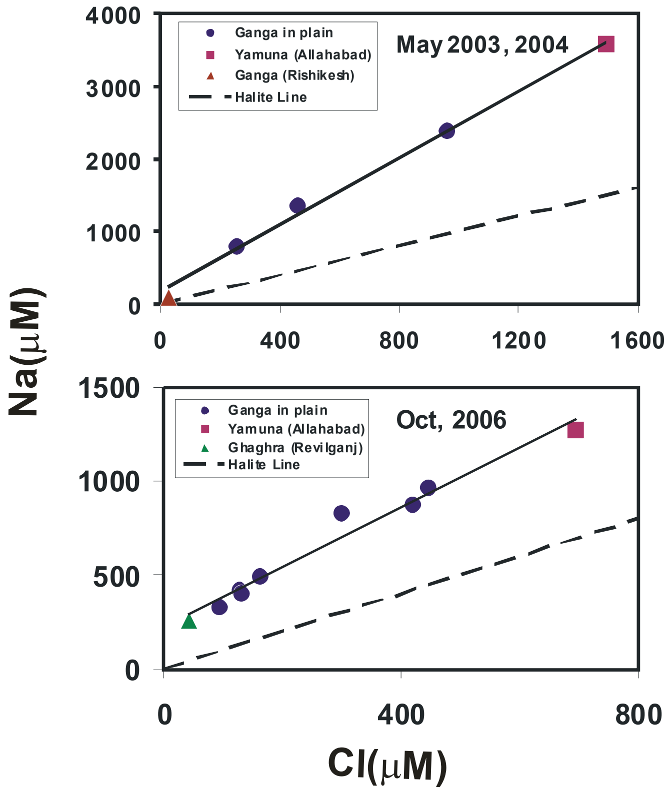


Fig-4.7: (Left) Variations in Na and Ca concentrations of the Ganga mainstream from its source to its outflow at Rajmahal. In the May samples Na in the Ganga increases sharply at Varanasi after confluence with the Yamuna, highlighting the importance of the Yamuna in contributing to Na (and other major ions) to the Ganga mainstream. Ca concentrations also show similar trend along the Ganga mainstream however magnitude of variations is much less, this may be an affect of calcite supersaturation which maintain Ca concentration around ~800 µM.

Fig-4.8: (Right) Variation of Na with Cl of the Ganga mainstream. The data seem to be a result of two end member mixing, the high concentration member (Yamuna) and the low concentration member characterized by the Himalayan tributaries.

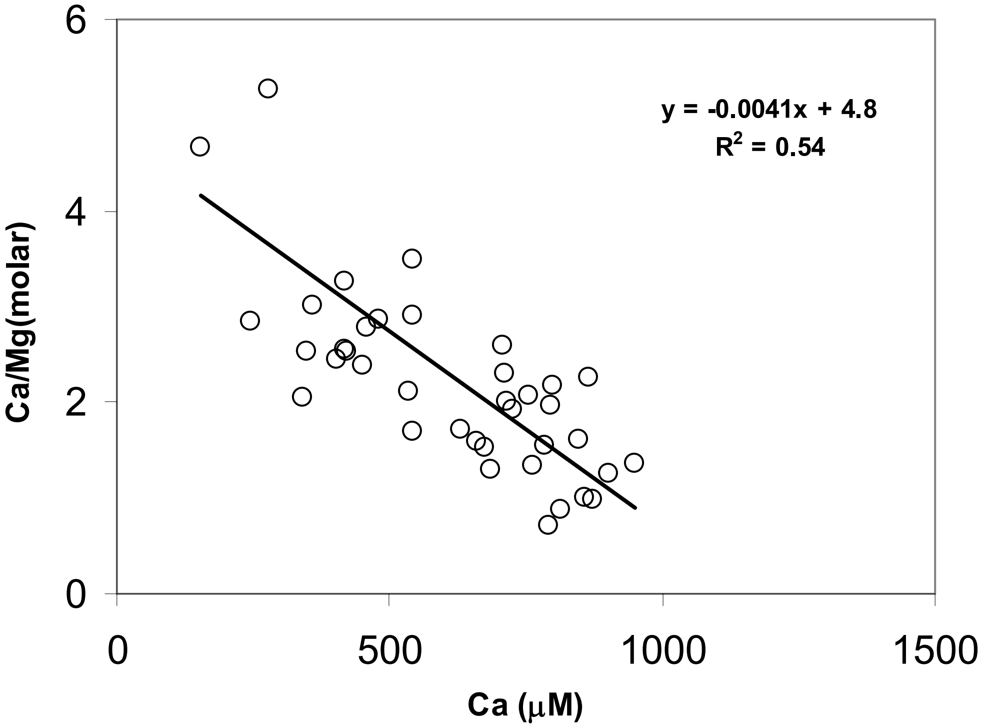


Fig-4.9: Variation of Ca/Mg with Ca in the Ganga river and its tributaries.

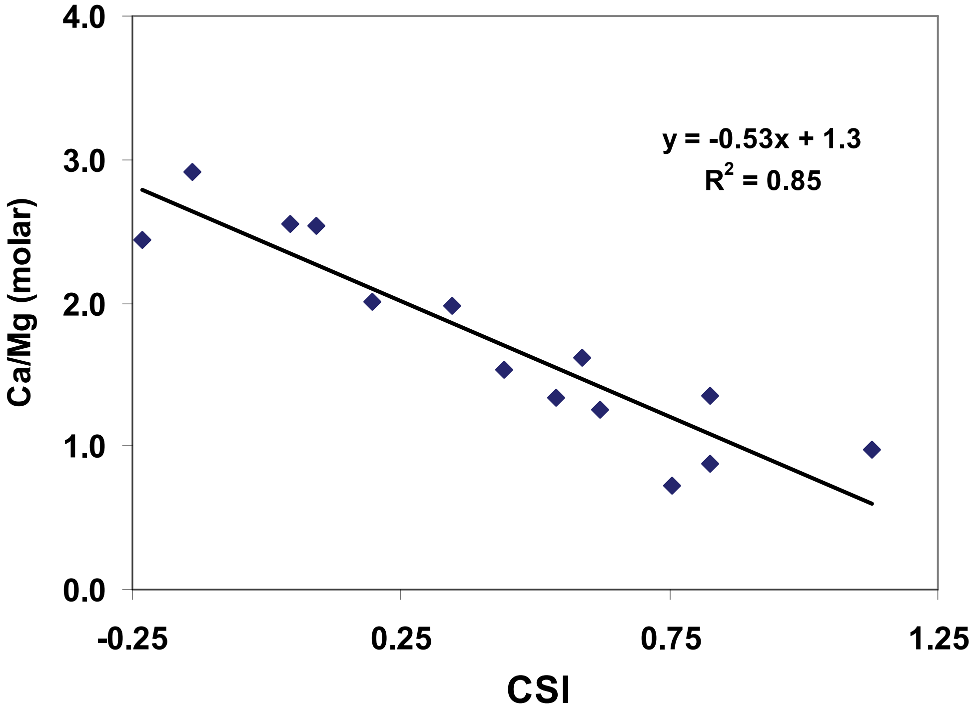


Fig-4.10: Plot between Ca/Mg and Calcium saturation Index (CSI) of water samples from the Ganga and its tributaries. The decrease in Ca/Mg with Ca and CSI can be a result of Ca removal via calcite precipitation.

4.3 Chemical Erosion in the Plain, Peninsular and the Himalayan Sub-Basins of the Ganga

Dissolved major ions in rivers are derived primarily from two sources atmospheric deposition and chemical weathering of various lithologies of the basin (Holland, 1978; Meybeck, 1979; Stallard and Edmond, 1983; Stallard, 1995; Meybeck, 2005). In this study, the atmospheric contribution to Ganga water chemistry is evaluated separately for the Ganga headwaters in the Himalaya and for the Ganga and its tributaries in the plain. The calculation assumes that all chloride in river water samples with lowest Cl is of atmospheric origin. For the head waters, the average of three river samples with the lowest chloride yield a value of (10 ± 2) μM for contribution from precipitation (Table-4.1). For the Ganga and its tributaries in the plain, the average chloride of the samples BR06-901, -705, and -501, (32 ±15) μM, is taken as typical contribution from rain. This value takes into consideration the effect of evapotranspiration as it is based on measured river water concentration. The rain water contribution to chloride is calculated to range from ~13% to 49% in the remaining Ganga headwater samples (Table-4.1) and 2 to 67 % for rivers in the plain. The atmospheric contributions for Na, Mg and Ca are calculated from representative (element/Cl) ratios in precipitation (Table-4.6). For Na this averages ~6% for the head waters and ≤ 11% for all these elements for rivers in the plain. Chloride in excess of atmospheric input in rivers has to be derived from other sources, such as hot springs and evaporites. Hot springs are known to be an important source for excess chloride (over atmospheric contribution) for the Ganga head waters (Evans et al., 2001; Bickle et al., 2003). In the plain and peninsular sub-basins of the Ganga, evaporites in the form of alkaline and saline salts in soils could be relatively more important (Singh et al., 2004, 2008) especially in the drainage basins of the Yamuna, the Gomti and the Ganga downstream of Kanpur.

The Chemical Erosion Rates of cations $(\mathrm{CER})_{\mathrm{cat}}$ have been calculated based on atmospheric contribution corrected major ion and Sr abundances in rivers and their annual water discharge [$(\mathrm{CER})_{\mathrm{cat}} = \Sigma(\mathrm{x}_{\mathrm{i}}^{*}) \times \mathrm{Q}$, where x_i^* is Na, K, Mg and Ca abundances in river water corrected for rain input and evapotranspiration and Q is the runoff].

Table-4.6: Chemical composition of Rain water, ice and snow in the Himalaya and plain regions.

Sample	Na	K	Ca	Mg	Cl	NO_3	SO_4	Reference
Rain 1 (Dehradun)	0.2	0.8	0.7	0.4	3.2	-	4.5	Dalai et al., 2002
Rain 2 (Dehradun)	0.2	0.8	1.3	0.7	3.8	-	4.8	Dalai et al., 2002
Chhota Shigri (snow)	14	7	6	4	21	8	2	Nijampurkar et al., (1993)
Chhota Shigri (ice)	8	3	2.6	1.4	11	7	1.8	Nijampurkar et al., (1993)
Dokriani Bamak (snow)	10	3.4	4.2	2.4	19	3.4	6.8	Sarin and Rao (2002)
Himalaya (weighted average)	10	2.2	22	6.1	7.4	5.3	6.2	Galy & France-Lanord, 1999
Himalaya	**7.0**	**3.0**	**6.0**	**2.5**	**11.0**	**6.0**	**4.0**	
Roorkee	38.5	14.7	145.1	23.3	59.4	33.4	22.6	Hameed et al., 2006
Dayalbagh (suburban)	54.8	7.7	42	13.2	23.7	17.6	14.2	Saxena et al., (1996)
Gopalpura (Near Agra)	19.4	2.5	67.2	39.2	30.6	42.6	7.7	Satsangi et al., (1998)
Plain (weighted average)	35	6.6	34	9	29	4.8	19	Galy & France-Lanord, 1999
Rain water (Plain)	**37**	**8**	**72**	**21**	**36**	**25**	**16**	

Table-4.7: Major ion and Sr fluxes from the basins of the Ganga and its tributaries

River	Location	Date	Discharge 10^{12} ℓ	Area 10^3 km^2	Basin[#]	Flux (10^4 tons yr^{-1})							
						Na*	Na**	K*	Mg*	Ca*	Sr	$(\Sigma Flux)_{cat}$	$(\Sigma Flux)^*_{cat}$
Ganga	Rishikesh	May-03	23.9	21.7	H	5.5±1.8	4.2±1.8	3.8±1.1	9±3	40±12	0.15±0.05	58±12	57±12
Ghaghra	Revilganj	Oct-06	94.4	128	H+P	48±17	46±17	27±8	84±26	307±98	1.13±0.34	466±103	464±103
Ghaghra[&]	Kotilaghat	Nov-94	63.4	57.6	H	28±9	25±9	11±3	66±20	226±68	0.72±0.22	331±71	328±71
Ghaghra			31	70.4	P	20±19	21±19	16±9	18±33	81±119	0.41±0.40	135±126	136±126
Gandak	Hazipur	Oct-06	52.2	46.3	H+ P	13±6	12±5	17±5	37±12	137±45	0.49±0.15	204±47	203±47
Gandak[&]	Narayanghat	Jun-93	49.4	31.8	H	12±4	6.1±4	9.8±2.9	29±9	118±35	0.41±0.12	169±37	163±37
Gandak			2.8	14.5	P	0.2±6.8	5.9±6.8	7.2±5.9	8±15	19±57	0.08±0.19	34±60	40±60
Gomti	Ghazipur	Oct-06	7.4	30.5	P	23±7	18±7	3.8±1.1	15±5	24±8	0.18±0.05	66±12	61±12
Chambal[&]	Dholpur	Sep-82	30	129	Pe	39±12	21±13	6.2±1.9	23±7	93±30	0.6±0.18	161±33	143±34
Betwa[&]	Hamirpur	Nov-83	10	46	Pe	34±11	27±11	2.2±0.7	14±4	38±12	0.3±0.09	88±17	81±17
Yamuna	Allahabad	Oct-06	93	366	H+Pe+P	266±82	124±93	31±9	97±30	230±76	2.2±0.66	624±116	482±124
Yamuna	Batamandi	Oct-98	10.8	9.8	H	6.2±1.9	4.8±1.9	2.2±0.7	13±4	44±13	0.17±0.05	66±14	64±14
Yamuna			82.2	356	Pe+P	259±82	119±93	29±9	84±30	189±77	2±0.66	561±117	421±125
Yamuna				124	P	94±29	74±30	15±5	61±19	97±31	0.72±0.22	267±47	247±47
Yamuna				232	Pe	165±87	45±98	13±10	23±36	90±83	1.33±0.70	291±126	171±133
Son	Koilawar	Oct-06	31.8	71.3	Pe+P	29±10	23±10	5.3±1.6	18±6	61±21	0.26±0.08	113±24	107±24
Kosi	Dumarighat	Oct-06	62	74.5	H+P	20±8	20±8	17±5	23±8	91±32	0.25±0.08	151±34	151±34
Ganga	Rajmahal	Oct-06	380	935	H+Pe+P	262±89	210±90	111±33	237±76	996±329	3.73±1.12	1607±351	1554±351

* Corrected for rain input and evapotranspiration

** Corrected for rain input and halite ($Na^{**} = Na_{riv} - Cl_{riv}$)

[&]: Data from Galy and France-Lanord (1999) and Sarin et al. (1999)

$(\Sigma Flux)^*_{cat} = (\Sigma Flux)_{cat}$ corrected for Na from halite

[#]: H: Himalayan, P: Ganga plain, Pe: peninsular drainage

Table-4.8: Major ion and cation Erosion rates in plain, peninsular and Himalayan sub-basins

River	Location	Date	Discharge	Area	Basin[#]	Erosion Rate (tons km^{-2} yr^{-1})							
			10^{12} ℓ	10^3 km^2		Na*	Na**	K*	Mg*	Ca*	Sr	$(CER)_{cat}$	$(CER)^*_{cat}$
Ganga	Rishikesh	May-03	23.9	21.7	H	2.5± 0.8	1.9 ± 0.8	1.8 ± 0.5	4.1 ± 1.2	18 ± 6	0.07± 0.02	27± 6	26 ± 6
Ghaghra	Revilganj	Oct-06	94.4	128	H+P	3.8 ± 1.3	3.6 ± 1.3	2.1 ± 0.6	6.6 ± 2.0	24 ± 8	0.09 ± 0.03	36 ± 8	36 ± 8
Ghaghra[&]	Kotilaghat	Nov-94	63.4	57.6	H	4.9 ± 1.5	4.3 ± 1.6	1.9 ± 0.6	11.5 ± 3.4	39 ± 12	0.13 ± 0.04	57 ± 12	57± 12
Ghaghra			31	70.4	P	2.8 ± 2.7	3.0 ± 2.7	2.3 ± 1.2	2.6 ± 4.6	12 ± 17	0.06 ± 0.06	19 ± 18	19 ± 18
Gandak	Hazipur	Oct-06	52.2	46.3	H+ P	2.8 ± 1.3	2.6 ± 1.1	3.7 ± 1.1	8.0 ± 2.6	30 ± 10	0.11 ± 0.03	44 ± 10	44 ± 10
Gandak[&]	Narayanghat	Jun-93	49.4	31.8	H	3.8 ± 1.2	1.9 ± 1.4	3.1 ± 0.9	9.1 ± 2.7	37 ± 11	0.13 ± 0.04	53 ± 12	51± 12
Gandak			2.8	14.5	P	0.1 ± 4.7	4.1 ± 4.7	5.0 ± 4.1	5.5 ± 10.1	13 ± 40	0.06 ± 0.13	24 ± 41	28 ± 41
Gomti	Ghazipur	Oct-06	7.4	30.5	P	7.5 ± 2.3	5.9 ± 2.4	1.2 ± 0.4	4.9 ± 1.5	8 ± 3	0.06 ± 0.02	22 ± 4	20 ± 4
Chambal[&]	Dholpur	Sep-82	30	129	Pe	3.0 ± 1.0	1.6 ± 1.0	0.5 ± 0.1	1.8 ± 0.6	7 ± 2	0.05 ± 0.01	12 ± 3	11 ± 3
Betwa[&]	Hamirpur	Nov-83	10	46	Pe	7.4 ± 2.3	5.9 ± 2.3	0.5 ± 0.1	3.0 ± 0.9	8 ± 3	0.07 ± 0.02	19 ± 4	18 ± 4
Yamuna	Allahabad	Oct-06	93	366	H+Pe+P	7.3 ± 2.3	3.4 ± 2.5	0.8 ± 0.3	2.7± 0.8	6 ± 2	0.06 ± 0.02	17 ± 3	13 ± 3
Yamuna	Batamandi	Oct-98	10.8	9.8	H	6.4 ± 2.0	4.5 ± 2	2.2 ± 0.7	13.3 ± 4.0	45 ± 14	0.17 ± 0.05	67 ± 14	65 ± 14
Yamuna			82.2	356	Pe+P	7.3 ± 2.3	3.3 ± 2.6	0.8 ± 0.3	2.4 ± 0.9	5 ± 2	0.06 ± 0.02	16 ± 3	12 ± 4
Yamuna				124	P	7.6 ± 2.4	6.0 ± 1.8	1.2 ± 0.4	4.9 ± 1.5	8 ± 3	0.06 ± 0.02	22 ± 4	20 ± 4
Yamuna				232	Pe	7.1 ± 3.8	1.9 ± 4.2	0.6 ± 0.4	1.0 ± 1.5	4 ± 4	0.06 ± 0.03	13 ± 5	7± 6
Son	Koilawar	Oct-06	31.8	71.3	Pe+P	4.1 ± 1.3	3.2 ± 1.4	0.7 ± 0.2	2.5 ± 0.8	9 ± 3	0.04 ± 0.01	16 ± 3	15 ± 3
Kosi	Dumarighat	Oct-06	62	74.5	H+P	2.7 ± 1.0	2.7 ± 1.0	2.3 ± 0.7	3.1 ± 1.0	12 ± 4	0.03 ± 0.01	20 ± 5	20 ± 5
Ganga	Rajmahal	Oct-06	380	935	H+Pe+P	2.8 ± 1.0	2.2 ± 1.0	1.2 ± 0.4	2.5 ± 0.8	11 ± 4	0.04 ± 0.01	17 ± 4	17 ±4

* Corrected for rain input and evapotranspiration

** Corrected for rain input and halite ($Na^{**}= Na_{riv}-Cl_{riv}$)

[&]: Data from Galy and France-Lanord (1999) and Sarin et al. (1999)

$(CER)^*_{cat} = (CER)_{cat}$ corrected for Na from halite

[#]: H: Himalayan, P: Ganga plain, Pe: Peninsular drainage

Table-4.9: Cation Erosion Fluxes and rates from the Ganga sub-basins*

Sub-basin	River	Date	Location	Water discharge	Drainage Area	$(\Sigma Flux)_{cat}$	$(\Sigma Flux)^*_{cat}$	$(CER)^*_{cat}$	
				10^{12} ℓ	10^3 km^2	10^4 tons yr^{-1}		tons km^{-2} yr^{-1}	mm kyr^{-1}
Himalaya									
	Yamuna	Oct-98	Batamandi	10.8	9.8	66	64	65±14	
	Ganga	May 03	Rishikesh	23.9	21.7	58	57	26±6	
	Ghaghra	Nov-94	Kotilaghat	63.4	57.6	331	328	57±12	
	Gandak	Jun-93	Narayanghat	49.4	31.8	169	163	51±12	
	Total				**121**	**624**	**612**		**20±3**
Plain									
	Gomti	Oct-06	Ghazipur	7.4	30.5	66	61	20±4	
	Yamuna		Plain		124	267	247	20±4	
	Ghaghra		Plain	31	70.4	135	136	19±18	
	Gandak		Plain	2.8	14.5	34	40	28±41	
	Total				**239**	**502**	**484**		**8±2**
Peninsular									
	Yamuna	Oct-06	Allahabad		232	291	171	7±6	
	Son	Oct-06	Koilawar	31.8	71.3	113	107	15±3	
	Chambal[&]	Sep-82	Dholpur	30	129	161	143	11±3	
	Betwa[&]	Nov-83	Hamirpur	10	46	88	81	18±4	
	Total				**303**	**404**	**278**		**3.7±1.8**
Ganga									
	Ganga	**Oct-06**	**Rajmahal**	**380**	**935**	**1607**	**1554**	17±4	**6.6±1.5**

*: for data sources see Table-4.7

[&]: These rivers are not considered in **Total** estimates

Two approaches have been used for calculating $(\mathrm{CER})_{\mathrm{cat}}$. One is based on rivers flowing through a single sub-basin, e.g. Gomti (Plain), Ganga at Rishikesh (Himalaya) and Chambal (peninsular). The second approach is based on flux by difference and uses data from rivers flowing through multiple sub-basins, e.g. the Ghaghra and the Gandak (Himalaya and plain) and the Yamuna (Himalaya, penisular and plain). In this case knowledge of elemental fluxes along the course of the river, at or near the exits of individual sub-basins is required. In this case the $(\mathrm{CER})_{\mathrm{cat}}$ from a particular sub-basin is calculated using the relation:

$$((CER)_{\mathrm{cat}})_i = \frac{\sum(F_t - F_j)}{A_i} \qquad \text{……………………} \quad (4.1)$$

where, F is the elemental/cation flux (tons yr^{-1}), A is the drainage area (km^2); i and j are the two sub-basins contributing to the total flux F_t. For majority of rivers, the chemistry of Oct 2006 samples (Tables-4.1& 4.2) have been used for calculating F_t, whereas F_j is based on available data in literature. For example, in the case of Ghaghra F_t is the measured flux at Revilganj and F_j is the Himalayan flux calculated from the data of Galy and France-Lanord (1999) for the sample at Kotilaghat, collected in November 1994. The calculated elemental fluxes and $(\mathrm{CER})_{\mathrm{cat}}$ are given in Tables 4.7-4.9.

(i) Ganga plain

The Gomti river which has its entire drainage in the plain, provides one estimate for elemental fluxes and $(\mathrm{CER})_{\mathrm{cat}}$ from the Ganga plain. More estimates of $(\mathrm{CER})_{\mathrm{cat}}$ in the plain can be derived from the Ghaghra and the Gandak data at Revilganj and Hazipur respectively, as at these locations both these rivers have part of their drainage in the plain. The elemental fluxes and $(\mathrm{CER})_{\mathrm{cat}}$ at these sampling sites are composites of contributions from the Himalayan and the Ganga plain sub-basins. From these composite fluxes, $(\mathrm{CER})_{\mathrm{cat}}$ in the Ganga plain, is derived by subtracting the Himalayan contribution based on eqn. (4.1).

The estimates (Figs.-4.11, 12; Table-4.8) show that $(\mathrm{CER})_{\mathrm{cat}}$ for the Gomti, Ghaghra and the Gandak plains are roughly similar ~21 tons km^{-2} yr^{-1}, the fluxes of individual elements, however, vary typically by factors of 2-4 and do not seem to show any discernible trend with run off. The major difference in the erosion rate (tons $km^{-2}yr^{-1}$) is for Na with highest for the Gomti plain (7.6 tons km^{-2} yr^{-1}) and the lowest for the Gandak plain (0.2 tons km^{-2} yr^{-1}). In the Gandak, the Na flux measured at Hazipur nearly matches that reported at Narayanghat (Galy and France-Lanord, 1999) close to the exit of the river in the Himalayan sub-basin. This leads to infer that Na supply to the Gandak from the plain sub-basin is quite low, possibly due to limited occurrence of saline/alkaline soils in this sub-basin coupled with limited silicate erosion.

(ii) Peninsular Sub-basin

The Chambal, Betwa and the Son data provide elemental fluxes and $(CER)_{cat}$ for the peninsular sub-basin of the Ganga. The Chambal and Betwa represent the western peninsular region, dominated by the Deccan traps and Vindhyan whereas the Son from the eastern peninsula drains mainly Vindhyan and the Archean crust. In addition, the Yamuna data also have been used to determine fluxes and erosion rates of its peninsular basin after making appropriate corrections for contributions from its Himalayan and Ganga plain sub-basins. The contribution from the Himalayan sub-basin is calculated from the data of Dalai et al. (2002) at Batamandi sampled during October 1999 (Table- 4.2). The contribution from the Ganga plain to the Yamuna fluxes is estimated by scaling the Gomti fluxes based on drainage area. The $(CER)_{cat}$ for these peninsular basins are roughly similar, 12-19 tons km^{-2} yr^{-1} (Table-4.8). The elemental fluxes among these basins vary by a factor of ~2 (Table-4.7, Figs-4.11, 12). The Chambal (Dholpur) and Betwa (Hamirpur) data used in these calculations are from Sarin et al. (1989).

(iii) Himalayan Sub-basin

The elemental fluxes and $(CER)_{cat}$ for the Himalayan sub-basin of the Ganga is based on data of the Ganga at Rishikesh, Yamuna at Batamandi, Ghaghra at Kotilaghat and the Gandak at Narayanghat. The Ghaghra and the Gandak data are from Galy and France-Lanord (1999).

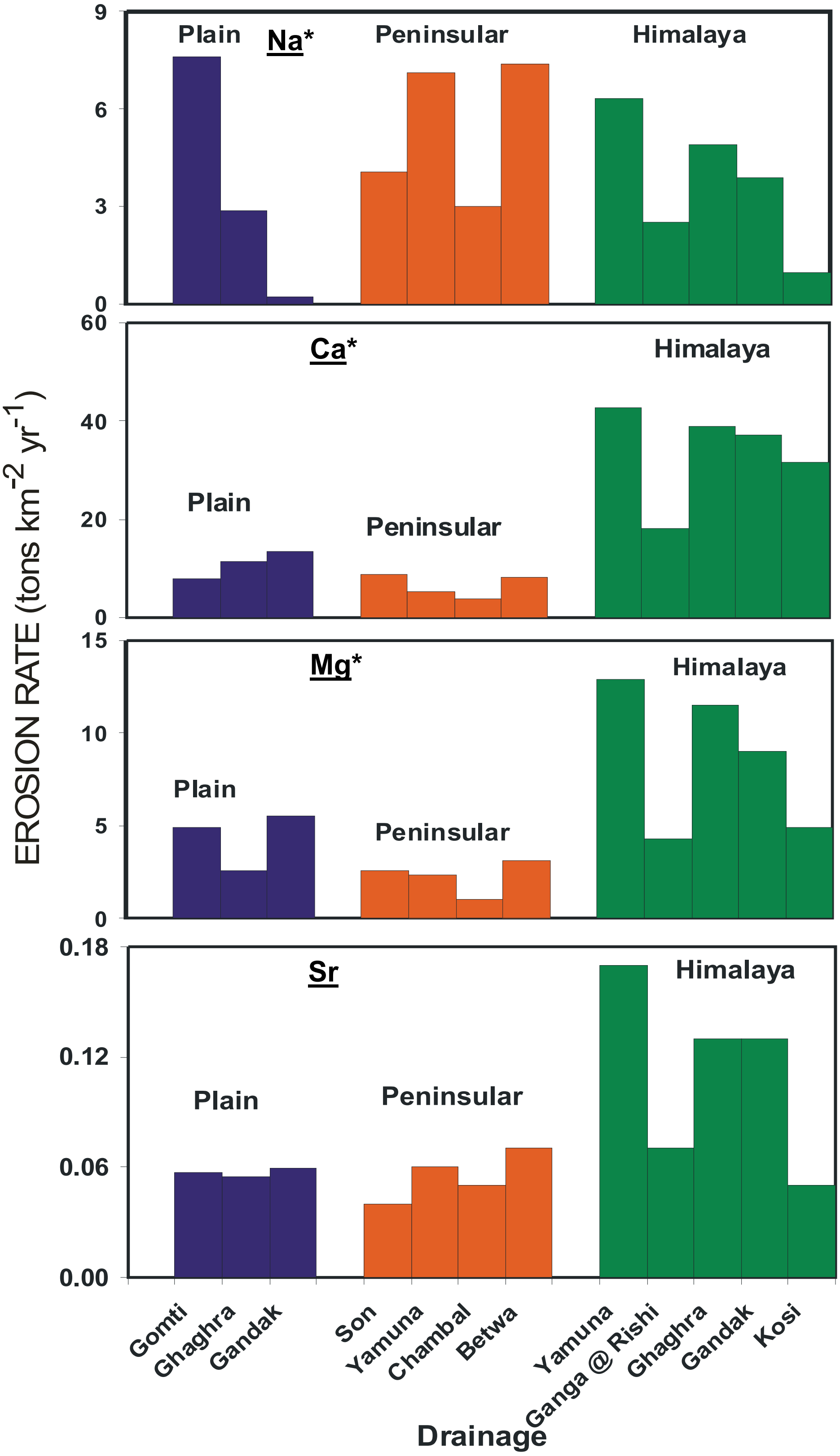


Fig-4.11: Erosion rates of Na*, Ca*, Mg*, and Sr in the various sub-basins of the Ganga. The Ca, Mg and Sr erosion rates are higher in the Himalaya compared to that in the plain and peninsular drainages; whereas Na* erosion rate is similar in all the sub-basins (except for the Gandak).

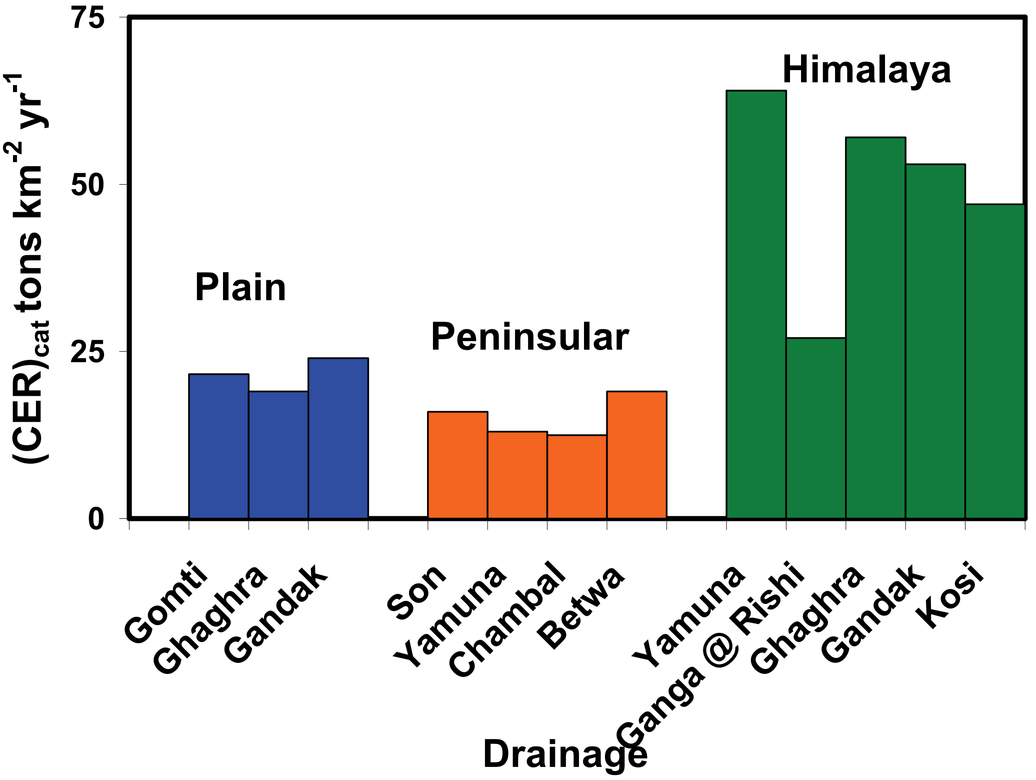


Fig 4.12: Chemical Erosion rates of cations, $(CER)_{cat}$, in the various sub-basins of the Ganga. $(CER)_{cat}$ in the Himalaya is 2-3 times higher than those in the peninsular and plain drainages. The higher runoff and relief of the Himalayan drainage are the major contributors to this difference.

Among the three sub-basins of the Ganga $(\mathrm{CER})_{\mathrm{cat}}$ is the highest for the Himalayan drainage, ranging from 27 to 67 tons km^{-2} yr^{-1}, with the Yamuna basin having the highest erosion and the Ganga at Rishikesh, the lowest (Fig-4.12). Kosi data has not been included in this range as it is a composite of erosion in the Himalayan and plain sub-basins.

It is seen from Tables-4.8 and 4.9 that the erosion rates of elements from the plain and peninsular sub-basins are generally lower than that from the Himalaya. The area weighted $(\mathrm{CER})_{\mathrm{cat}}$ in the peninsular region is ~13 ± 4 tons km^{-2} yr^{-1}, within errors similar to that for the Ganga plain, ~21 ± 6 tons km^{-2} yr^{-1}. It is also seen that the $(\mathrm{CER})_{\mathrm{cat}}$, particularly $(\mathrm{CER})^{*}_{\mathrm{cat}}$ [$(\mathrm{CER})^{*}_{\mathrm{cat}}$ is $(\mathrm{CER})_{\mathrm{cat}}$ corrected for halite input of Na. Na** = $(Na_{riv} - Cl_{riv})$] of the Chambal, Betwa and the Yamuna peninsular basins bracket the erosion rate for the Son basin, despite the fact that the peninsular drainages of the Yamuna and its tributaries have significant exposures of more easily weatherable Deccan basalts and alkaline/saline soils compared to granite/gneisses and shales/slates of the Son drainage. The similarity in their $(\mathrm{CER})_{\mathrm{cat}}$ therefore has to be assigned to other causes, such as cumulative effect of higher rain fall, runoff and relief in the Son catchment compared to the peninsular drainage of the Yamuna and its tributaries.

It is interesting to note that though the overall $(\mathrm{CER})_{\mathrm{cat}}$ of the peninsular and plain drainages of the Ganga is 2-4 times lower compared to that of its Himalayan zone (Table-4.9), their erosion fluxes (tons yr^{-1}) are comparable. This is because the total drainage area of the peninsular and plain zones of the Ganga basin is ~4 times the area of its Himalayan sub-basin. The higher $(\mathrm{CER})_{\mathrm{cat}}$ in the Himalayan basin is attributable to its high relief and runoff coupled with its higher physical erosion as has been observed for other river basins from this region (Singh and France-Lanord, 2002; Thiede et al., 2004; Singh et al., 2008). In addition, the endoreic nature of the peninsular and plain basins and their semi-arid climate retards chemical erosion in them.

Galy and France-Lanord (1999), based on fluxes of major elements from the headwater basins of the Gandak and the Ghaghra in the Himalaya and that of the Ganga in Bangladesh, estimated that the sum of silicate and carbonate erosion rates in the Ganga plain is ~5 mm kyr^{-1}, 5-12 times lower than that in the Himalayan drainage and 2-3 times lower than that in the Ganga drainage as a whole. They also noted that chemical erosion rates in the Himalaya are dominated by carbonate erosion and hence are dependent on the abundance of carbonates in the basin, for example in the Bheri basin the carbonate erosion rate was more than an order of magnitude higher than its silicate erosion rate. $(\mathrm{CER})^{*}_{\mathrm{cat}}$, estimated in this study (Table-4.8) can be compared with the sum of silicate and carbonate erosion rate estimates of Galy and France-Lanord (1999). The results (Table-4.9) show that the average erosion in the Himalayan sub-basin, ~20±3 mm yr^{-1}, is twice the average in the plain, ~8±2 mm yr^{-1}, similar to the trend reported by Galy and France-Lanord (1999). The lower erosion rate in the plain is attributable to its lower runoff, 0.3 m yr^{-1}, ~3 times less than that in the Himalaya. This interpretation differs from that of Galy and France-Lanord (1999) who have explained the lower erosion in plain in terms of its lower carbonate content. The observation that Ca and Mg concentrations in the Gomti is similar to or more than that in the Himalayan tributaries of the Ganga is an indication that the role of carbonates in contributing to the major ion chemistry of all these rivers is roughly similar. Further, the occurrence of carbonates in the form of kankar, calcretes and detrital carbonates dispersed through out the plain in varying concentrations (Agarwal et al.,1992; Singh et al.,2004; Singh, 1996) suggest that paucity of carbonates available for weathering may not be a controlling factor for the low chemical erosion rate of the region. A more likely cause, therefore, for the low chemical erosion is the low runoff in the plain compared to that in the Himalaya. Further, the lower relief of the plain reduces the intensity of physical erosion, which in turn can retard chemical erosion.

The October 2006 data further show that the sum of the elemental fluxes measured in various tributaries of the Ganga rivers exceeds those measured in the Ganga mainstream at its outflow, Rajamahal (Tables-4.7 and 4.9). This could either be due to interannual variations in water discharge of the rivers or that part of the dissolved material is retained in the plain. If the water discharge of various rivers for the year 2006 is different from the average value (Rao, 1975; http://www.grdc.sr.unh.edu) used for calculation then such imbalances can occur. Similarly, there are evidences for the retention of river solutes in the plain in the form of alkaline/saline soils. Among the major ions measured in rivers, the largest discrepancy is in the budget for Na, a major constituent of saline/alkaline soils. However, as these soils are formed mainly during summer when the rivers are nearly dry their impact during October, when the river stage is high, is expected to be minor.

(iv) Uncertainties in the estimates of fluxes and erosion rates

The fluxes of major elements and their erosion rates from the sub-basins of the Ganga and its tributaries are estimated, as mentioned earlier, by two approaches. The sources of errors in these estimates are those associated with (i) analytical measurements. This is generally ≤ ± 5% (ii) use of October or June or November concentration data as the annual average.

Time series analysis of the Yamuna at Allahabad, Ganga at Rishikesh and the Alaknanda at Srinagar (Tripathy, unpublished data), based on biweekly/monthly sampling during 2004-05 show that the October and November concentrations of different elements on average are ~ 45% higher than the annual discharge weighted value and that of June ~55% higher. Thus, the use of concentration data measured in October or November or June would on average overestimate the annual discharge weighted concentration (and hence flux) by ~50%. This is a scaling factor for deriving annual flux from measurements made during these months (iii) inter annual variations in elemental fluxes from the different sub-basins. This is particularly important for the flux by difference approach (eqn. 4.1) as the elemental fluxes for the different sub-basins were obtained during different years. There is, however no data on yearly variations in elemental fluxes from the locations of interest, hence the uncertainties arising from this source are estimated indirectly. A major contributor to variations in elemental fluxes is inter-annual variations in water discharge.

Table-4.10: Variability in the annual water discharge of the Ganga and Yamuna during different time periods

Period	Discharge (m^3s^{-1}) Average	±1σ	%Deviation	Reference
Ganga at Farrakka				
1950-1960	12492	1557	12	UNESCO, 1971
1965-1973	10996	2652	24	UNESCO, 1993
1991-2001	9993	2552	26	http://rbis.sr.unh.edu
Yamuna at Allahabad				
1991-2001	2494	1318	53	http://rbis.sr.unh.edu
Average uncertainty			29	

This data for the Ganga at Farakka for the periods 1950-1960 and 1965-1973 (UNESCO, 1971, 1993) yield ineterannual variations of 12 % and 24 % respectively (Table-4.10). Similarly, for the Yamuna a value ± 53% is calculated based in its discharge data at Allahabad for the period 1990-2001 (http://rbis.sr.unh.edu/explorer/basin.cgi?basin=00000&bounds=75,90,19,34&point=0.00,0.00&type=eh_discharge_pristine&date=&town=1&pot=0&map_switch=1). The variations in elemental fluxes are expected to be less than that in water discharge as elemental concentrations in general are negatively correlated with water discharge. Therefore, based on these data and above considerations an uncertainty of ± 30% has been assigned to the elemental flux data. This uncertainty is propagated suitably for estimating fluxes by difference and cation erosion rates (eqn. 4.1). As will be discussed later, the sum of fluxes from the Ganga tributaries differ from that measured at its out flow on average by ~30%; possibly due to interannual variations in elemental fluxes. As an independent exercise, interannual variations in concentrations of major ions (Na, K, Mg and Ca) were estimated for the Ganga at Rishikesh for which data were available for the month of September for several years, 1982, (Sarin et al., 1989), 1996 (Krishnaswami et al., 1999; Bickle et al., 2003), 1999 (Dalai et al., 2002; Bickle et al., 2003, 2004;Tripathy et al., 2008). These data yield an average uncertainty of ± 27% (Table-4.11).

Table-4.11: Interannual variation in the major ion concentrations of the Ganga river at Rishikesh (for the month of September)

Element	**1982**	**1996**	**1996**	**1996**	**1999**	**1999**	**2004**	**2004**	Mean	±1σ	%
Na	145	65	61	103	82	76	84	157	97	36	37
K	40	43	37	40	37	37	58	48	42	7	17
Ca	353	355	316	412	409	397	330	516	386	64	16
Mg	153	122	103	235	146	150	137	285	166	62	37
							Average uncertainty				27

Source: Sarin et al., 1989 ; Krishnaswami et al., 1999 ; Dalai et al., 2002; Bickle et al., 2003 ;Tripathy (unpublished data)

The elemental fluxes and $(CER)_{cat}$ for the Himalayan sub-basins based on data of the Ganga (Rishikesh), Yamuna (Batamandi), Ghaghra (Kotilaghat) and the Gandak (Narayanghat), the Ganga plain from the data of the Gomti and the peninsular basin from the Chambal and Betwa data (Tables-4.7-4.9) all have an uncertainty of ~ ±30%. The errors associated with estimates of fluxes and erosion rates of the Ghaghra and the Gandak plains and the peninsular basin of the Yamuna are derived by suitably propagating the uncertainties associated with fluxes of individual sub-basins and eqn (4.1).

4.4 Silicate Erosion Rates (SER) and associated CO_2 Consumption in the Ganga Basin:

Many earlier studies (Edmond and Huh, 1997; Singh et al., 1998; Gaillardet et al., 1999; Galy and France Lanord, 1999; Krishnaswami et al., 1999; English et al., 2000; Dalai et al., 2002; Jacobson et al., 2002; Oliver et al., 2003; Bickle et al., 2005; Hren et al., 2007) used major ion concentration and Sr isotope composition of rivers to derive silicate weathering contribution to their solute composition. Among the various dissolved component in rivers other than for Si (H_4SiO_4) which is entirely of silicate origin, all other major ions have multiple sources, as listed below.

$$Na_r = Na_a + Na_{sil} + Na_e \quad ....(4.2)$$

$$Ca_r = Ca_a + Ca_{sil} + Ca_e + Ca_c \quad ....(4.3)$$

$$Mg_r = Mg_a + Mg_{sil} + Mg_c \quad ....(4.4)$$

where the subscript r, represents river, a – atmospheric, e – evaporite including alkaline/saline soils, sil – silicate, c – carbonate. The relative contribution from different sources for a particular cation may vary from basin to basin. Therefore, to derive silicate weathering contributions to river solutes, contributions from sources other than silicates have to be suitably accounted.

The contribution from different lithologies to the major ion abundance of rivers is generally assessed following either the forward model (Singh et al., 1998; Galy and France-Lanord,1999; Krishnaswami et al.,1999) or the inverse model (Negrel et al.,1993; Gaillardet et al.,1999; Millot et al., 2003; Wu et al., 2005; Moon et al., 2007). The forward model relies on the use of Na corrected for cyclic salts and evaporites, ($Na^{**} = Na_r - Cl_r$) as an index of silicate weathering contribution along with assigned values for Ca/Na and Mg/Na released from silicates to rivers. The Ca/Na and Mg/Na ratios are generally taken to be the ratios in parent rocks, i.e. catchment silicates. The model therefore assumes congruent release of Na, Mg and Ca from silicate of the drainage basin to river water. In the inverse model, the contributions of different sources are derived from the measured concentrations based on budgets for elemental raios (Negrel et al., 1993; Gaillardet et al., 1999; Millot et al., 2003; Moon et al., 2007). In this approach, a priori knowledge of “representative” end member is not critical, as the models are suitably designed to derive the best estimates for elemental ratios and the contribution of various end members to river water chemistry. The reliability of the forward model to derive silicate weathering contribution requires that Na** as calculated is sourced *only* from silicates. In this study, this assumption is very likely to be valid for rivers in the Himalayan basin where silicate, atmospheric deposition and halite dissolution are likely to be the only sources of Na. In contrast in the Ganga plain, particularly in the Yamuna, Gomti and Ganga (downstream Allahabad) basins, the occurrence of saline, alkaline or sodic soils containing various sodium salts can serve as additional sources of dissolved Na. As the magnitude of this Na contribution is difficult to assess, estimate of silicate erosion rates based on Na** may not be quite reliable for these river basins. This constrains the determination of silicate erosion rates in the Ganga plain and peninsular sub-basins and therefore in the Ganga basin as a whole, based on the water chemistry downstream of Allahabad.

In this study, therefore Na** based silicate weathering rates are derived only for the Ganga head waters and its Himalayan tributaries (the Ghaghra, the Gandak and the Kosi). The estimates are based on the water chemistry of samples collected in May 2004 at Bhagirathi (Devprayag), Alaknanda (Devprayag), Ganga (Rishikesh), Ghaghra (Faizabad), Gandak (Barauli) and Kosi (Dumarighat). Further these estimates use values of 0.7±0.3 and 0.3±0.2 respectively for Ca/Na and Mg/Na molar ratios for release from silicates to rivers. (based on their abundances in granites/gneisses; soil profiles and selected streams, Krishnaswami et al., 1999). The calculated silicate derived cations $(\Sigma Cat)_{sil}$ [defined as $(\Sigma Cat)_{sil} = (Na_{sil} + K_r + 0.7Na_{sil} + 0.3Na_{sil})$ moles] is given in Table (4.12). From this, the fraction of silicate contribution to the major ion abundances of river is estimated to vary from 14 to 40% with an average of 28±8%. Highest silicate fraction was in the Kosi (~40%) and lowest in the Gandak (~14%) which is consistent with the observation about low IC in the Kosi and high IC in Gandak sediments. Previous studies (Krishnaswami et al., 1999) have also reported values in the range of ~30% for silicate fraction in the Ganga at Rishikesh during March/April. As sampling was done during low stages of the rivers, the estimated erosion rates are expected to be higher than the annual average. The Na** concentration in the Ganga at Rishikesh during May is 33% higher than the discharge weighted annual concentration (Tripathy unpublished data). This coupled with K and SiO_2 abundances show that SER in the Himalayan tributaries are ~15% more if calculated based on May data than the annual average.

Abundances of major cations in rivers originating from weathering of silicates (Na_{sil}, K_{sil}, Ca_{sil} and Mg_{sil}) and silica along with runoff are the parameters needed to estimate the silicate erosion rates. Silicate erosion rates (SER) have been calculated for the Ganga mainstream and its major Himalayan tributaries based on the relation: $[(SER) = (\Sigma(Cat)_{sil} + SiO_2].Q)$ where Q is the run off and $\Sigma(Cat)_{sil}$ is the sum of silicate derived Na, K, Mg, and Ca as calculated above $\Sigma(Cat)_{sil}$ and SiO_2 are expressed in mg ℓ^{-1}.

In the above calculation only samples which have chloride concentration less than or equal to100 μM are considered for estimation of SER as an additional caution to minimize the impact of evaporites contributing to Na. Assuming an average density 2.7 $g.cm^{-3}$ for silicate rocks, SER vary from ~4 ±0.4 mm kyr^{-1} (~12 ±1.1 tons $km^{-2} yr^{-1}$) for Kosi to ~7 ±0.5 mm kyr^{-1} (~18 ±1.4 tons $km^{-2} yr^{-1}$) in the Gandak basin. Among the various sub-basins of the Ganga the Gandak river basin has the highest SER (Table-4.12). This result is consistent with the observation that this basin also has the highest physical erosion rate among the Ganga sub-basins (Chapter-3, Singh et al., 2008) and hence attesting the fact that physical erosion promotes chemical erosion. The CO_2 consumption in the basins of Himalayan tributaries and Ganga headwaters is roughly same, $(4 \pm 1) \times 10^5$ mole $km^{-2} yr^{-1}$. It is also born out from the results that in the Ganga basin the Ghaghra sub-basin is the major sink for atmospheric CO_2. Results of this study on silicate erosion rates are similar within uncertainties, to the earlier work on Central Himalyan rivers, the Trishuli, Bheri and Narayani etc (Galy and France-Lanord, 1999) varying between 7±3 to 11±2 mm kyr^{-1}.

Table-4.12: Silicate erosion rates (SER) and associated CO_2 consumption in the Ganga headwaters and its Himalayan tributaries.

Sample	**River**	**Location**	**Area**	**Discharge**	**$(TDS)_{sil}$**		**SER**				**$(\Sigma cat)_{sil}$**		**CO_2 drawdown**	
							(i) tons km^{-2} yr^{-1}		(ii) mm kyr^{-1}				10^5 (mole km^{-2} yr^{-1})	
			km^2	10^{12} ℓ.y^{-1}	mg $ℓ^{-1}$	±		±		±	μE$ℓ^{-1}$	±		
Headwaters														±
RW03-3	Bhagirathi	Devprayag	7800	8.3	14.5	1.1	15.5	1.1	6	0.4	334	70	3.6	0.7
RW03-4	Alaknanda	Devprayag	11800	14.1	11.4	0.8	13.6	0.9	5	0.3	253	51	3.0	0.6
RW03-2	Ganga	Rishikesh	19600	22.4	12.5	0.8	14.3	1.0	5	0.4	272	55	3.1	0.6
Tributaries														
BR-354	Ghaghra	Faizabad	127950	*63.4*	33.5	2.9	16.6	1.4	6	0.5	986	190	4.9	0.9
BR-334	Gandak	Barauli	46300	*49.4*	17.2	1.3	18.3	1.4	7	0.5	380	87	4.1	0.9
BR-327	Kosi	Dumarighat	74500	48.2	26.1	2.3	16.9	1.5	6	0.6	724	155	4.7	1.0
BR06-501	Kosi	Dumarighat	74500	48.2	18.7	1.7	12.1	1.1	4	0.4	544	114	3.5	0.7

Average silicate density ~2.7 g cm^{-3} ; $(TDS)_{sil}$ is the sum of cations derived from silicate and SiO_2.

4.5 Impact of Chemical erosion in the plain and peninsular sub-basins on estimates of silicate erosion rates in the Ganga basin and elemental fluxes

One of the important findings of this study is that the peninsular and plain sub-basins contribute significantly to the fluxes of major ions transported by the Ganga to the Bay of Bengal. Among the major ions the contribution of Na, sourced mainly from alkaline/saline soils, is the dominant. It is also observed that Na in the plain and peninsular rivers is in considerable excess over Cl. The ultimate source of this Na in excess of chloride, in the absence of anthropogenic input, is silicate weathering. In spite of this, the use of Na** (= Na_r-Cl_r) as a proxy to determine silicate erosion rates is in doubt, as its relation to contemporary silicate weathering of these river basins is unclear. The use of Na** to estimate silicate weathering rates is based on the assumption that its abundance in rivers is due entirely to present day silicate weathering of their basins. This requirement may be violated if part of Na in the Ganga and its tributaries is a result of leaching saline/alkaline soils formed in the past and/or from excessive use of groundwater (Goldsmith and Hildyard, 1984). In such cases the silicate erosion rates derived from Na** can be overestimates of the present day value. The aerial coverage of saline/alkaline soils in the plains and peninsular sub-basins of the Ganga are reported to be steadily increasing with time (Goldsmith and Hildyard, 1984) suggesting that the formation of these soils is an ongoing process. The uncertainty in the use of Na** precludes the calculation of silicate erosion rates of the Ganga downstream of Kanpur and its tributaries such as the Gomti and the Yamuna in the Ganga plain. This ‘Na source problem’ can be more widespread and can compromise estimation of silicate erosion rates of river basins from semi-arid regions and with poor drainage. The Bhima river and it tributaries draining the Deccan Traps of India fall in this category. Similarly, Singh et al., (2006) have demonstrated that in the Brahmaputra, a significant source of Na (and Sr) is saline deposits and lakes from cold and arid regions of Tibet. The peninsular and plain sub-basins supply most of Na and 40 to 80 % of Ca, Mg and Sr (in that order) to the Ganga at its outflow at Rajmahal. The Ca<Mg<Sr trend may be due to preferential removal of dissolved Ca from rivers by calcite precipitation.

4.6 Impact of saline/alkaline salts in Sr geochemistry of the Ganga in plain and erosion rates of Sr in the Ganga sub-basins.

Sr concentration in the Ganga mainstream vary widely, from 467 nM in Kosi (October 2006) to 5889 nM in the Yamuna (May 2004). The Yamuna value is one of the highest Sr concentrations measured in the Ganga system. The concentration of Sr in the Ganga mainstream varies linearly with Na with a very strong positive correlation with Na (Fig-4.13). This trend can be explained in terms of two end member mixing, the Himalayan (Ganga at Rishikesh) and the Yamuna (Allahabad). The correlation also highlights the role of the Yamuna in regulating the concentration of both Na and Sr in the Ganga main stream, most likely through recycling Na and Sr as a part of saline/alkaline soils and raises additional concerns on the potential application of Sr as a proxy of silicate weathering in the Ganga basin downstream of Allahabad.

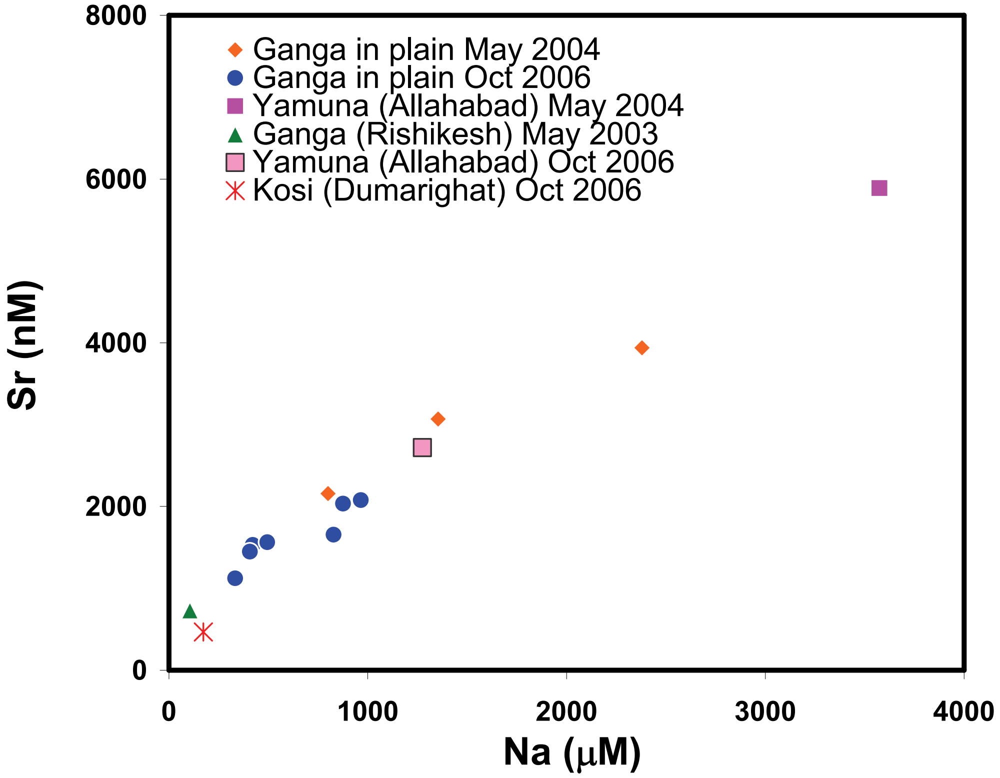


Fig-4.13: Variation of Sr with Na in the Ganga mainstream. Strong positive correlation between Na and Sr is a result of mixing between the Yamuna (higher concentration) with the Himalayan tributaries (lower concentration). The strong correlation brings out the role of recycling of both Na and Sr.

The erosion rate of Sr in the plain and peninsular drainage varies within narrow range of 0.04 to 0.07 tons km^{-2} yr^{-1} (Table-4.8).The Sr erosion rates in the plain sub-basins of the Gandak and the Ghaghra are similar to that of the Gomti and yield an average value of 0.06 tons km^{-2} yr^{-1}. For the Himalayan drainage, Sr erosion rate follows the trend of chemical erosion rates with the highest in the Yamuna basin and the lowest in the Kosi (Tables-4.7, 4.8). The low chemical and Sr erosion rates in the Kosi are attributable to lower carbonate exposures in its Himalayan sub-basin. This interpretation is also consistent with the ^{87}Sr/^{86}Sr data which shows that among the Ganga (Rishikesh), Ghaghra, Gandak and the Kosi, the most radiogenic Sr is in Kosi waters, ^{87}Sr/^{86}Sr: 0.74806 (May 2004), 0.75732 (October 2006). This can be explained in terms of limited supply of unradiogenic carbonate Sr to the rivers and therefore lesser dilution of radiogenic silicate Sr. Another factor that can contribute to the lower erosion in the Kosi drainage is its lower runoff compared to other Himalayan drainages (Singh et al., 2008), this explanation , however is not consistent with Sr isotope data.

Sr flux of the Ganga (Table-4.13) at its outflow, Rajmahal based on the October 2006 sample is ~3.7×10^4 tons yr^{-1} with ^{87}Sr/^{86}Sr ~0.72707. This compares with reported annual flux of 4.1×10^4 tons yr^{-1} Sr with ^{87}Sr/^{86}Sr of 0.7239 (Krishnaswami et al.,1992). This yields ^{87}Sr flux of 0.27×10^4 tons yr^{-1} from the Ganga. The Yamuna contributes about 60% of the total Sr and ^{87}Sr to the Ganga at its outflow followed by the Ghaghra which contribute ~30% of Sr. In the Yamuna, more than 90% of Sr is derived from the peninsular and plain drainages. These sub-basins of the Yamuna is also the major supplier of ^{87}Sr to the Ganga despite the fact that an important component of the lithology in the peninsular drainage is Deccan Traps, which is quite unradiogenic in Sr (Peng et al.,1998). The collective flux of Sr from all the tributaries is 4.7×10^4 tons yr^{-1}, ~25% more compared to that measured in the Ganga at its outflow, 3.7×10^4 tons yr^{-1} (Table-4.7). The flux weighted ^{87}Sr/^{86}Sr of the Ganga tributaries is 0.7235 for October 2006, marginally lower than the measured value of 0.7271 at its outflow at Rajmahal. Inter-annual variations in water discharge of the tributaries could be a potential cause for this difference.

Table-4.13: Sr concentration and flux for the Ganga and its tributaries[+]

River	Location	Discharge 10^{12} ℓ yr^{-1}	Sr (Conc.) nM	Sr Flux 10^4 ton yr^{-1}
Gomti	Gazipur	7.4	2717	0.18
Son	Koilwar	31.8	944	0.26
Yamuna	Allahabad	93	2717	2.21
Ganga	Rishikesh	23.9	731	0.15
Ghaghra	Revilganj	94.4	1373	1.14
Gandak	Hazipur	52.2	1064	0.49
Kosi	Dhumarighat	62	467	0.25
Ganga	Rajmahal	380	1122	3.73

[+] Based on Oct 2006 samples, except Ganga at Rishikesh which was sampled in May 2003.

For example, if the Yamuna water flux was low by ~25% in 2006 compared to the average value of 93 km^3 yr^{-1} (Rao, 1975) the agreement between the measured flux at Rajmahal and the sum of the fluxes from the tributaries would be better.

4.7 Behaviour of Ca and Sr in the Ganga river system: Clues from Ca/Sr and $^{87}Sr/^{86}Sr$ of waters.

One of the important issues in quantifying the budget of Sr in river waters in terms of its contribution from different sources pertains to the knowledge of the behaviour of dissolved Ca. If Ca behaves conservatively, the apportionment of Sr concentration between silicates and carbonates would be valid, however, if it is non-conservative then the apportionment based on the forward model (Krishnaswami and Singh, 1998; Galy and France-Lanord, 1999; Krishnaswami et al., 1999) would under estimate the carbonate component of Ca and hence that of Sr. The impact of loss of Ca is also not considered in the inverse model.

In this study, efforts have been made to assess the behaviour of Ca in the Ganga system rivers based on their $^{87}Sr/^{86}Sr$ and Ca/Sr. The approach is based on the assumption that only two sources silicate and carbonate weathering contribute to dissolved Ca and Sr. This assumption is expected to be satisfied better in rivers draining the Himalayan sub-basin of the Ganga. This is because the Ganga in plain receives dissolved Sr and Ca from its other sub-basins such as the plain and peninsular regions (Rai et al., 2008; Rengarajan et al., 2008) which compounds the Ca and Sr budgets. The “Ca Behaviour” problem has been addressed in some of the earlier work (Jacobson et al., 2002; Bickle et al., 2003, 2005; Tipper et al., 2008) which show that a significant part of dissolved Ca in the Ganga system rivers are removed via calcite precipitation.The $^{87}Sr/^{86}Sr$ and Ca/Sr of the Ganga headwaters and its tributaries in the Himalaya are plotted in the Fig-4.14. The water samples have a wide range of $^{87}Sr/^{86}Sr$ values, from ~0.7266 to ~0.7896 with Ca/Sr molar ratios generally $<1x10^3$. Also shown in the plot are the values for the two end members, the Pre Cambrian (Pc-C) carbonates and Himalayan silicates. The $^{87}Sr/^{86}Sr$ and Ca/Sr of Pc-C carbonates are from Singh et al. (1998) whereas for silicates, it is based either on bank sediments analysed in this study (Chapter-3) or on the compilation of available data on $^{87}Sr/^{86}Sr$ of silicate and carbonate rocks in various river basins in the Ganga drainage of the Himalaya (Table-4.14; Galy, 1999; Bickle et al., 2001; Harris et al., 1998; Oliver et al., 2003; Quade et al.,2003). The data in Table-4.14 though show significant variation in $^{87}Sr/^{86}Sr$ among the river basins, their range and average overlaps with those measured in this study for silicates in the bank sediments (Fig-4.14).

Table-4.14: $^{87}Sr/^{86}Sr$ of silicates and carbonates of various basins in the Ganga drainage

Basin	Silicates	±σ	(n)	Carbonates	±σ	(n)	Reference
Bhagirathi	**0.783**	**0.005**	3	**0.711**	**0.004**	4	This work, Singh et al., 2008
Alaknanda	**0.758**	**0.004**	3	**0.717**	**0.009**	6	This work, Singh et al., 2008
Ghaghra	**0.773**	**0.012**	7	**0.726**	**0.007**	6	Bickle et al., 2001, 2005 Galy, 1999; This work Singh et al., 2008
Gandak	**0.744**	**0.013**	18	**0.725**	**0.016**	10	Galy, 1999; This work Singh et al., 2008
Kosi	**0.816**	**0.025**	4	**0.715**	**0.000**	5	Oliver et al., 2003; This work Singh et al., 2008
Mean	**0.775**	**0.027**		**0.720**	**0.007**		

It is seen from Fig-4.14 that most of the samples from the Bhagirathi and the Kosi fall within the mixing envelope of silicate-carbonate suggesting that in these waters, the $^{87}Sr/^{86}Sr$ and Ca/Sr are consistent with two end member mixing and therefore both Ca and Sr can be considered as behaving conservatively.

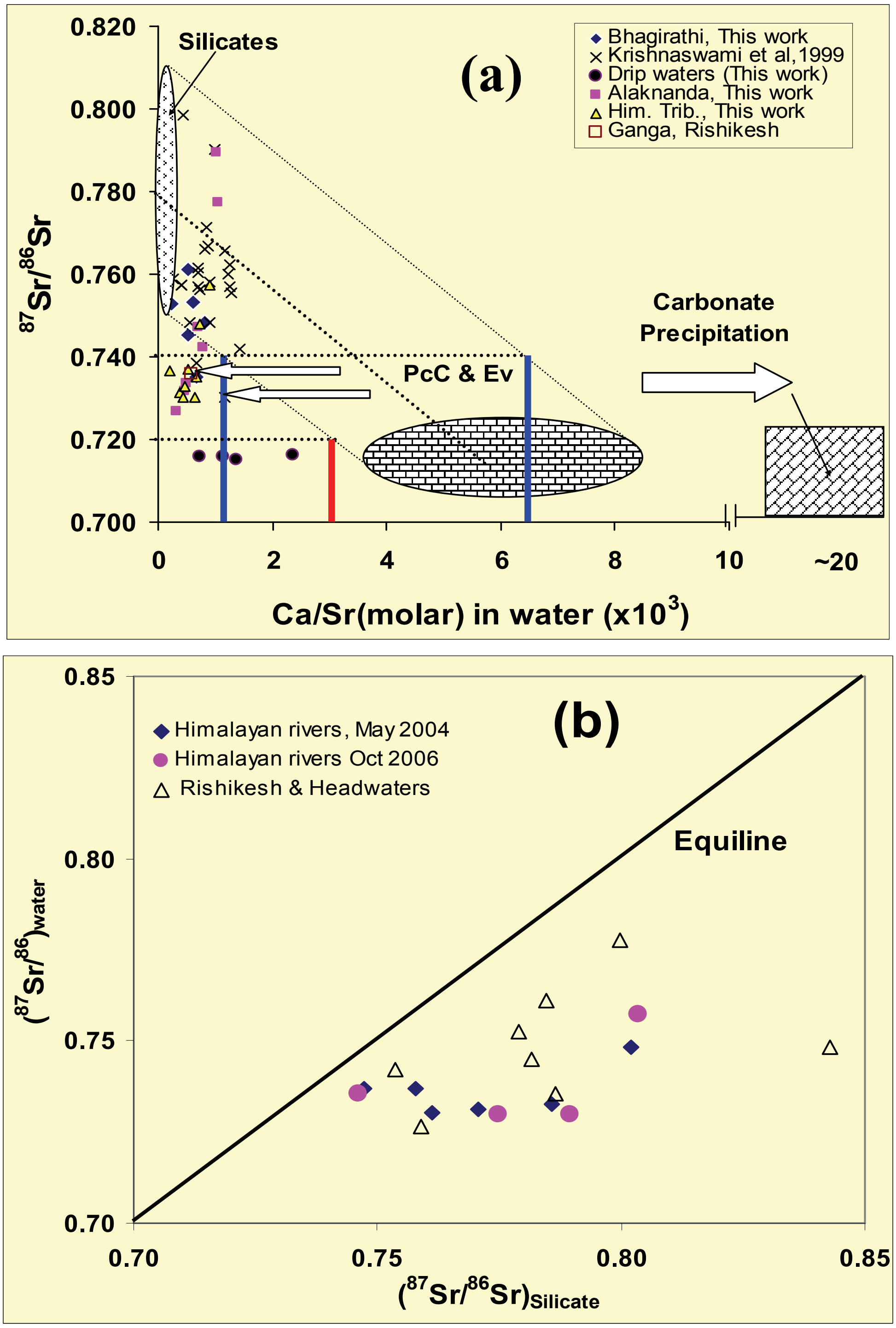


Fig-4.14:(a) Plot of ^{87}Sr/^{86}Sr vs Ca/Sr in river waters of the Ganga system from the Himalayan sub-basin. The values for the two end members are also shown. The arrows show the direction of movement of Ca/Sr in water following precipitation of $CaCO_3$. Precipitation decreases the Ca/Sr ratio in water without affecting the ^{87}Sr/^{86}Sr.

(b) ^{87}Sr/^{86}Sr of the Ganga water and silicate component of bank sediments. The data show that ^{87}Sr/^{86}Sr of waters are much lower than those in silicate due to mixing with unradiogenic Sr from carbonate. The deviation from 1:1 line has been used to derive the silicate: carbonate supply ratio for Sr and from that the Ca budget.

This is consistent with the reported observations that these rivers are under saturated in calcite (this work; Quade et al., 1997, 2003; Jacobson et al., 2002; Tipper et al, 2006) In contrast, many samples particularly from the Alaknanda, Ghaghra and the Gandak fall even below the lower bound of the mixing envelope. This observation suggests that the Ca/Sr in these water samples is less than that would be expected for their $^{87}Sr/^{86}Sr$. The trend in Fig-4.14 is similar to those reported by Krishnaswami and Singh, (1998) for the head waters of the Ganga and Dalai et al., (2003) for the Yamuna in the Himalaya. These authors attributed the trend to the supply of Sr to water from an additional source with low $^{87}Sr/^{86}Sr$ and Ca/Sr, potential candidates being evaporites/phosphates. Alternatively, removal of Ca from river water by precipitation of calcite can also serve as a mechanism to decrease Ca/Sr in water. This is because the precipitation of calcite preferentially removes Ca over Sr from water as the partition coefficient of Sr to calcite is <<1 (Banner 1995; Rimstidt et al., 1998). The low partition coefficient would yield carbonate precipitates with Ca/Sr higher than that in water.

To check on this, Ca, Mg, Sr and $^{87}Sr/^{86}Sr$ were measured in seepage/ dripping water and precipitated carbonates from regions adjacent to these waters. These data are presented in Table-4.15 and also plotted in Fig-4.14. As expected, the precipitated carbonates have $^{87}Sr/^{86}Sr$ similar to the source waters, with Ca/Sr ~2-20 times the water (Table-4.15) supporting the preferential removal Ca.

Thus the precipitation of $CaCO_3$ would decreases Ca/Sr in water relative to its original value. The impact of this decrease on $^{87}Sr/^{86}Sr$ and Ca/Sr plot would be to cause a shift in the data points away from the mixing line towards lower Ca/Sr (shown by arrows in Fig-4.14). The precipitation process does not change the $^{87}Sr/^{86}Sr$, as isotopic fractionation of Sr during the process is insignificant (Faure, 1986). Considering that for a two end member mixing Ca/Sr of water should fall within the mixing envelope if both Ca and Sr behave conservatively, an explanation for the data falling below the envelope is that Ca is lost from the dissolved phase via calcite precipitation. The extent of departure from the mixing line provides a means to estimate the magnitude of Ca loss. This is calculated based on the following relations.

$$f_p = \left(\frac{Ca_w}{Ca_0}\right) = \left(\frac{\left(\frac{Ca}{Sr}\right)_0}{\left(\frac{Ca}{Sr}\right)_w}\right)^{\left(\frac{1}{(K_d - 1)}\right)} \qquad \ldots\ldots\ldots\ldots\ldots\ldots \qquad (4.5)$$

where $\left(\frac{Ca}{Sr}\right)_0$ is the ratio prior to precipitation of calcite and $\left(\frac{Ca}{Sr}\right)_w$ is the measured value. $\left(\frac{Ca}{Sr}\right)_0$ is the (Ca/Sr) ratio expected for a given ^{87}Sr/^{86}Sr and is calculated from the $\left(\frac{^{87}Sr}{^{86}Sr}\right)$ - $\left(\frac{Ca}{Sr}\right)$ mixing line. For example, in samples with ^{87}Sr/^{86}Sr of 0.720, a (Ca/Sr)$_0$ of at least 3 is expected. Similarly for ^{87}Sr/^{86}Sr of 0.740, the (Ca/Sr)$_0$ is expected to be in the range of 1.3 to 6.5 (Fig-4.14). K_d is the relative distribution coefficient for Sr to Ca in calcite. f_p is the fraction of Ca left in river water after precipitation (Albarede, 1995).

Calculation of f_p has been carried out for the headwaters of the Ganga and its Himalayan tributaries (the Ghaghra, Gangdak and the Kosi). The latter group of rivers has part of their basin in the plain, where drainage is retarded. Samples from this study and from Krishnaswami et al. 1992 are plotted in Fig-4.14a. Several samples of this study and two samples from the study of Krishnaswami et al. (1992) from the Alaknanda fall out side the mixing envelope. The Ca loss calculated for samples which plot outside the mixing envelope in Fig-4.14a are listed in Table-4.15. Results of this study show that ~60-80% (Table-4.16) of initial calcium can be lost by precipitation as calcite in the Ghaghra and Gandak rivers during both summer (May 2004) and post monsoon (Oct 2006) samples. The observation that one of the Bhagirathi samples (RW03-8) also falls out side the mixing envelope is intriguing. Earlier studies (Bickle et al., 2005, Jacobson et al., 2002; Tipper et al., 2008) have also reported a high degree of Ca loss, ~70% for the Himalayan streams .This result highlights the role of calcite precipitation in determining the abundance of dissolved Ca in the Ganga and its tributaries.

Table-4.15: Chemical and isotopic composition of precipitated carbonates, evaporites and corresponding waters

Sample ID	Ca (%)	Sr µg g^{-1}	Ca/Sr (molar)x10^3	^{87}Sr/^{86}Sr	Sample ID	River Water	Sr nM	Ca µM	Ca/Sr (molar)x10^3	^{87}Sr/^{86}Sr
RS03-6[+]	39.3	219	3.9	0.75608	**RW03-7**	Gang Nani (spring)	2295	1516	0.7	0.75615
RS03-39	35.3	127	6.1	0.72190	**RW03-20**	Seepage water (Lokhandi)	1598	1323	0.8	0.72204
-	-	-	-	-	**RW03-21**	Seepage water (Lokhandi)	913	692	0.8	0.72615
RS03-34B[+]	28.6	34.6	18.1	0.71173	**RW03-17**	Dipping water (Sahashra Dhara)	16461	3687	0.2	0.71093
RS03-38	39.6	47.9	18.1	0.70976	**RW03-18**	Sulphur water (Sahashra Dhara)	84715	13773	0.2	0.70977
-	-	-	-	-	**RW03-19**	Stream water (Kempty Fall)	28607	4304	0.2	0.70950
RS03-35(evap)	22.3	131	3.7	0.71656						
RS03-36(evap)	22.6	148	3.4	0.71494						
RS03-6(L)		239		0.75609						
RS03-34B(L)		37.9		0.71134						

[+] Leached samples

Table-4.16: Ca loss due to calcite precipitation in Ganga system rivers.

			(Ca/Sr) µM/nM			**Ca loss**+
River	**Sample**	**Location**	$(Ca/Sr)_m$	$(Ca/Sr)_0$	**$^{87}Sr/^{86}Sr$**	(%)
Bhagirathi	RW03-5	Gangotri (Bhagirathi)	0.52		0.76101	nd
	RW03-8	Uttarkashi (Bhagirathi)	0.53	0.66	0.74512	21
	RW03-10	Ghanshyali (Bhilangana)	0.81		0.74828	nd
	RW03-9	Syansu Gad (Trib. Bhagirathi)	0.24		0.75268	nd
	RW03-3	Devpryayag (Bhagirathi)	0.61		0.75330	nd
	RW03-6	Glacer melt (Higher Himalaya)	0.67		0.73504	nd
Alaknanda	RW03-4	Devpryayag (Alaknanda)	0.49	1.74	0.73368	74
	RW03-11	Rudrapryayag (Alaknanda)	0.47		0.73158	nd
	RW03-12	Rudrapryayag (Mandakini)	0.69		0.74709	nd
	RW03-13	Birahi (Birhi tributary)	1.03		0.78955	nd
	RW03-14	Birahi (Birahi Ganga)	1.05		0.77738	nd
	RW03-15	Birahi (Alaknanda)	0.32	2.39	0.72662	88
	RW03-16	Pindar Valley (Pindar)	0.78	0.91	0.74231	15
Ganga	RW03-2	Rishikesh (Ganga)	0.57	1.54	0.73572	65
Ghaghra	BR06-901	Revilganj (Ghaghra)	0.63	2.07	0.73001	72
	BR-342	Revilganj (Ghaghra)	0.39	1.96	0.73125	82
	BR-354	Faizabad (Ghaghra)	0.47	1.81	0.73282	76
	BR-363	Gorakhpur (Rapti)	0.44	2.07	0.73009	81
Gandak	BR06-705	Hazipur (Gandak)	0.67	1.58	0.73526	60
	BR-334	Barauli (Gandak)	0.51	1.41	0.73707	66
	BR-311	Hazipur (Gandak)	0.19	1.44	0.73675	68
Kosi	BR06-501	Dumarighat (Kosi)	0.90		0.75732	nd
	BR-327	Dumarighat (Kosi)	0.73		0.74806	nd

+ Based on lower bound of end members; nd- no detectable loss

If such a loss of Ca indeed is prevalent then it would (i) underestimate Ca (and hence Sr) contribution to river waters from carbonates. This underestimation may be a cause for invoking the need for additional source of Sr to rivers (Krishnaswami and Singh, 1998; Dalai et al., 2003) and (ii) it would redistribute Ca from one sub-basin to another; for example Ca dissolved from the Himalaya sub-basin can precipitate in the plain.

An alternate approach to assess the Ca loss is by comparing the $^{87}Sr/^{86}Sr$ of river water with that of the silicate phase of bank sediments. This comparison is shown in Fig-4.14b. It is seen from the figure that Sr isotope ratios in water are significantly lower than those in silicates. The lower $^{87}Sr/^{86}Sr$ in water can be explained in terms of two end member mixing of Sr, that derived from radiogenic silicates and unradiogenic carbonates. Therefore, the deviation from the equiline is a measure of carbonate:silicate mixing proportion for Sr. From this and knowledge of (Ca/Sr) in silicate and carbonate end members the expected Ca abundance in water can be derived. This is compared with the measured Ca concentration to obtain Ca loss. The calculation is made for the Ganga at Rishikesh as given below, using end member values listed in Table-4.17. This approach assumes congruent release of both Sr and Ca from the end members and that release of Sr to water from silicates do not involve any change in its isotopic ratio. The ^{87}Sr/^{86}Sr of silicate end member (Table-4.17) is based on the bank sediment measured in this study. The uncertainties are based on replicate analysis and spatial and temporal variations.

Table-4.17 Calculation of silicate component for Rishikesh Sample

End member value	(^{87}Sr/^{86}Sr)	±	(Ca/Sr)	±
Silicate	**0.7865**	0.0056	220	120
Carbonate	**0.720**	0.007	5500	2000
Mixture				
River Water	**0.7357**	0.007	574	

Silicate component of Sr in Ganga at Rishikesh (f_{sil}) is given as:

$$f_{sil} = \frac{(R_{water} - R_{carb})}{(R_{sil} - R_{carb})} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4.6)$$

where R_i is the ^{87}Sr/^{86}Sr ratio in end members (carbonate and silicates) and mixture (river water). Calculation shows that the silicate component of Sr in the Rishikesh is about 24±13%. This coupled with (Ca/Sr) in silicate and carbonate end member yield a Ca loss ~90%. Extending the calculations to head waters of the Ganga and its Himalayan tributaries show that Sr_{sil} in them vary between 14 to 63% with an average of ~35±17 similar to the earlier reported estimates (Krishnaswami et al., 1999). All these estimates have significant uncertainties arising from wide range of Sr isotope composition and (Ca/Sr) ratio in the end members. For example, in the Rishikesh sample calculated Ca loss could be in the range of ~80% to 95% considering ±1σ uncertainties.

One of the major impacts of calcium removal from water via calcite precipitation is on the Sr budget. In the forward model, (Krishnaswami et al., 1999) Sr contribution from the carbonate is calculated as

$$Sr_c = \left(\frac{Sr}{Ca}\right)_c Ca_c \qquad \text{.........................} (4.7)$$

$$Ca_c = \left(Ca_r - Ca_{sil}\right) \qquad \text{.........................} (4.8)$$

where Ca and Sr are the calcium and strontium concentrations and the sucscripts, c, r and sil refer to carbonates, river and silicates. $\left(\frac{Sr}{Ca}\right)_C$ is the $\left(\frac{Sr}{Ca}\right)$ abundance ratio in Pc-C carbonates, Ca_r is the dissolved Ca concentration measured in rivers. If calcium is removed from dissolved phase then Ca_r would be less than that expected from weathering input. As a result, carbonate contribution of both Ca and Sr to rivers would be under estimated. The estimates of Ca_{sil} would not be affected as it is based on Na_{sil} and $\left(\frac{Ca}{Na}\right)_{sil}$ (Krishnaswami et al., 1999). Thus if there is 75% removal of Ca as calcite, it would result in underestimation of Sr_c by a factor of four. These arguments indicate that attempts to balance Sr budget in the Ganga system rivers should include the effect of calcite precipitation.

4.8 Biweekly variation in major ions, Sr concentration and $^{87}Sr/^{86}Sr$ of the Ganga

Erosion of river basins, particularly in tropical regions, are highly dependent on monsoon rains and exhibit significant variations as their discharge varies over orders of magnitude during an annual cycle. Therefore time series study of chemical erosion at a given site over an annual cycle will provide a more realistic estimate of chemical erosion in the basin than that based on a single sample collected during the year. Further, such a study will also yield a better understanding of the relation between chemical erosion and runoff in the basin as other parameters such as lithology and relief all remain nearly the same.

There have been a few studies on monthly/seasonal variation in major ion chemistry of the Ganga head waters and some of its tributaries in the Himalaya (Dalai et al., 2002; Bickle et al., 2003; Tipper et al., 2006; Chakrapani et al., 2008). These studies brought out the variability in the relative erosion rates of silicates and carbonates, with carbonate being weathered more intensely during monsoon. This result was explained in terms of faster dissolution kinetics of carbonate minerals (Tipper et al., 2006) variable relative input due to rainfall and glacial melt from different lithological units (Bickle et al., 2003), shorter interaction time for weathering during monsoon coupled with slower dissolution kinetics of silicates relative to carbonates (Rai and Singh, 2007) and enhanced chemical erosion due to higher physical erosion (Krishnaswami et al., 1999).

In this work, time series analysis of major ions and Sr isotopes have been made in the Ganga mainstream in the plain and its largest tributary the Yamuna. The Ganga at Allahabad after its confluence with the Yamuna shows large variation, over two orders of magnitude, in its discharge (185 to 20881 m^3s^{-1}). To characterize the impact of such a large variation in discharge on major ion abundances and chemical erosion, Ganga waters were sampled at Chhatnag (near Allahabad after the confluence with Yamuna). In addition, the Yamuna waters (near Yamuna bridge, Allahabad) were also sampled. Variations in the major ion composition of the Ganga and the Yamuna (Fig-4.15) show significant correlation for Na, Mg and Sr. The Na data however has more scatter. Ca abundance in the Yamuna and the Ganga do not show large variation.

4.8.1 General observations:

The following general observations have been made from these measurements. The abundances of all major elements and Sr decrease with increase in discharge in both the Yamuna and the Ganga (Fig-4.16). The chemistry of the Ganga at Chhatanag (near Allahabad) seems to be governed largely by mixing with the Yamuna (Fig-4.15). The Na data in the Ganga show a significant scatter in its concentration at low discharge. During this period much of Na in the Ganga is due to supply from the Yamuna mainly from saline/alkaline soils (section-4.2.2).

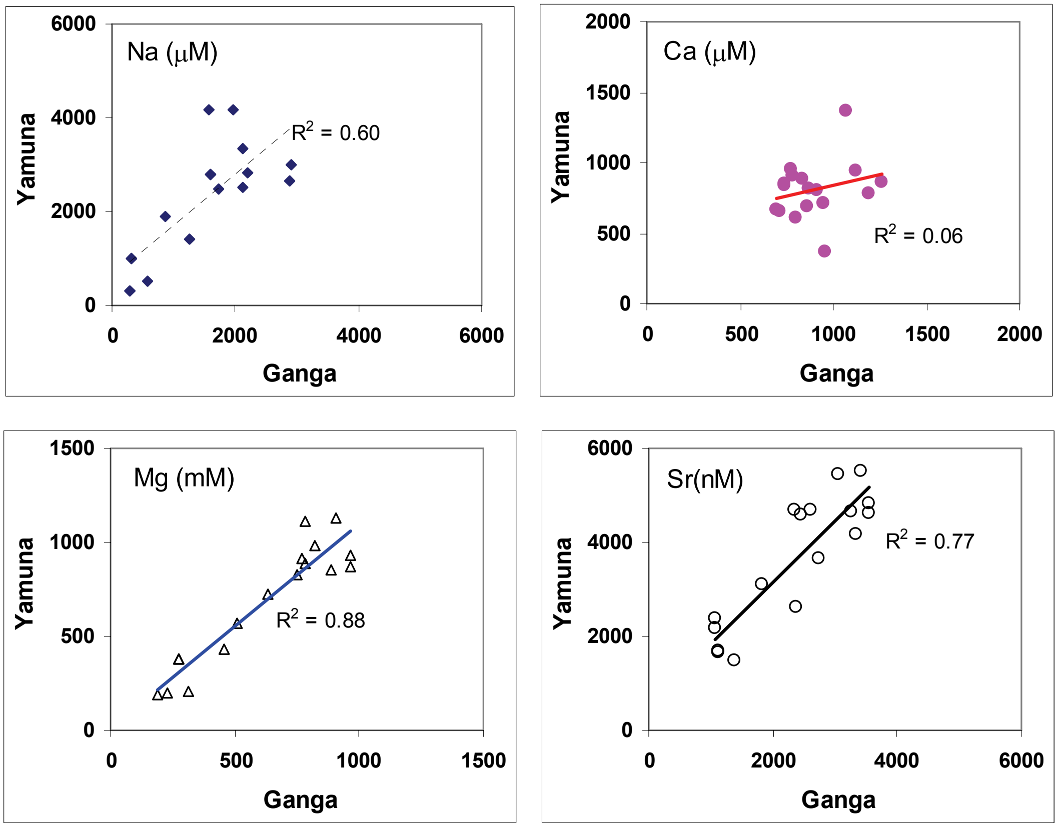


Fig-4.15: Co-variation in Na, Ca, Mg and Sr abundances in the Yamuna and the Ganga after its confluence with the Yamuna.

Variation in this supply can contribute the scatter in Na concentration at low discharge (Fig-4.16). Overall Na varies by a factor of ~10 from ~250 to 2858 μM and in general decreases with discharge. Ca concentrations also show a decreasing trend with discharge however its range is less pronounced (a factor of ~ 2) relative to Mg and Na. This is an indication that other factors such as calcite saturation or dissolution kinetics of carbonates (relative to silicates, the source for Na) may be controlling its abundance in these waters. These range in elemental concentration are much less than the range in discharge which is a factor of ~30. The results show that Na, Mg, Ca and Sr erosion rates from the basin range by a factor of ~5 for Na, ~6 for Mg, ~22 for Ca and 13 for Sr, if the anomalously high concentration sample of July15, 2005 is excluded. The erosion fluxes of various major ions and Sr are listed in Table-4.18 and plotted in Fig-4.17 for the date of sampling. The data show that flux estimated from single sampling can differ from the annual discharge weighted average by a factors of ~2-3 for Na*, Mg* and Sr and by a factor of ~5 for Ca* (* corrected for rain input).

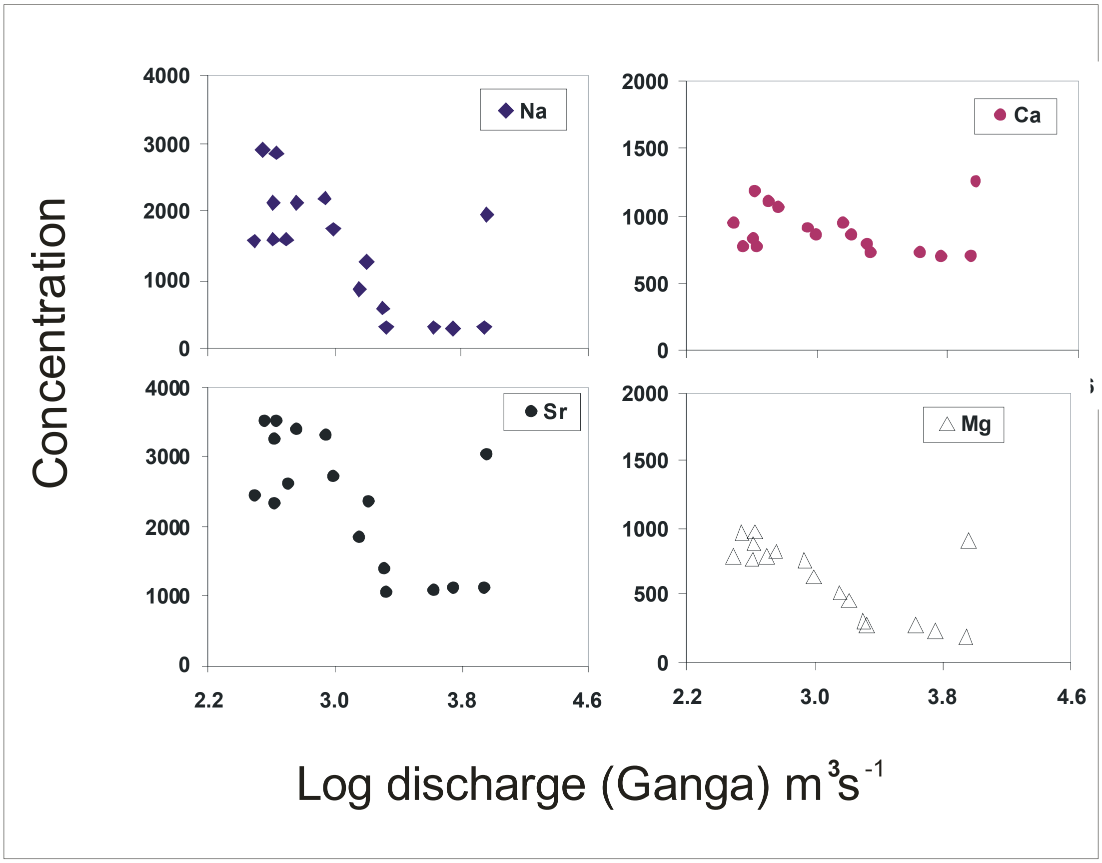


Fig-4.16: Variation in concentration of elements with discharge in the Ganga river at Chhatanag after the confluence with the Yamuna. Sharp peak in the elemental concentration is seen on the 15th July sample. Na, Ca and Mg concentrations are in µM and Sr in nM.

The annual erosion fluxes for Na*, Mg*, Ca* and Sr (Table-4.18) show that chemical erosion of different elements are season dependent with high values during monsoon. Annual fluxes for Ca* and Mg* flux calculated from September sample are similar to that of the average annual fluxes. This indicates that September sample can represent the yearly fluxes for Ca* and Mg*. However, chemical erosion flux of Na* in September shows variation lower by a factor of ~2. This most likely is due to inter annual variations. A unique feature of the results is the pronounced high in the abundances of Na, Mg, Ca and Sr (Fig-4.17) the Ganga samples collected on the July 15th during the peak discharge of the rivers.

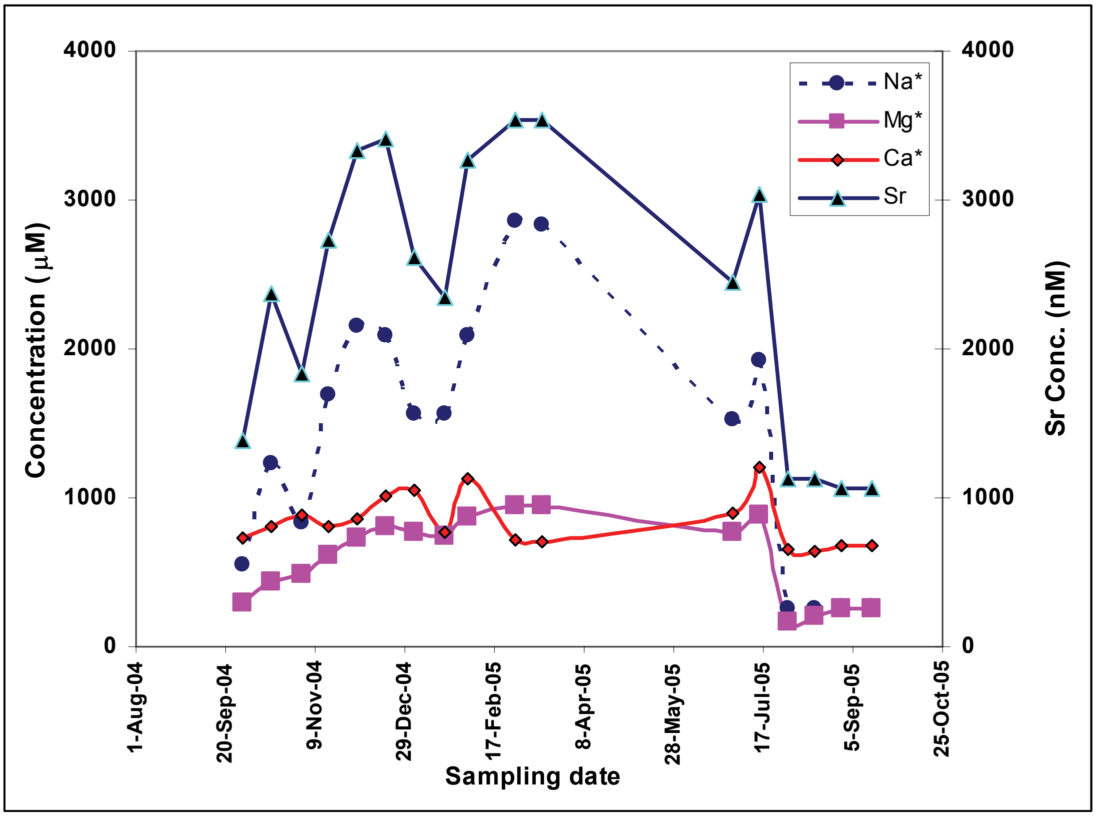


Fig-4.17: Temporal variation of dissolved elements (corrected for atmospheric input) in the Ganga river at Allahabad (After its confluence with Yamuna). The scales of Na, Mg and Ca is on the left and for Sr on the right.

One possible explanation for such a result is the solution of salts from saline/alkaline soils from the river basin during floods associated with early periods of monsoon. The higher abundances of Cl and SO_4 in the July 15th sample relative to the rest of the monsoon periods though is consistent with such a hypothesis, the role of such soils in contributing to increase in Ca needs to be assessed. Interestingly, Rai and Singh (2007) reported a sharp peak (15th June 2000) in the abundances of major ions in time series sampling over a period of one year of the Brahmaputra at Guwahati. This result was explained in terms of a flash flood in the Brahmaputra due to a natural dam burst in the Yigong River of Tibet.

Table-4.18: Chemical erosion fluxes of elements in Ganga at Allahabad (after the confluence with the Yamuna) expressed in tons $d^{-1.}$

Date	Sample	Discharge	Na*		Mg*		Ca*		Sr	
		m^3s^{-1}	μM	Flux	μM	Flux	μM	Flux	nM	Flux
30-Sep-04	RWG-1	2035	545	2204	292	1247	735	5183	1390	21
16-Oct-04	RWG-2	1624	1226	3956	438	1493	808	4544	2374	29
2-Nov-04	RWG-3	1441	828	2371	494	1493	885	4418	1832	20
16-Nov-04	RWG-4	978	1695	3295	613	1259	803	2721	2732	20
2-Dec-04	RWG-5	872	2158	3741	734	1344	855	2582	3333	22
18-Dec-04	RWG-6	575	2088	2387	803	971	1010	2013	3409	15
3-Jan-05	RWG-7	502	1562	1559	765	806	1057	1838	2621	10
20-Jan-05	RWG-8	411	1562	1275	750	647	774	1101	2351	7
2-Feb-05	RWG-9	417	2084	1725	871	762	1132	1633	3270	10
1-Mar-05	RWG-10	353	2858	2007	945	701	717	878	3536	9
16-Mar-05	RWG-11	426	2831	2398	950	851	711	1050	3544	11
30-Jun-05	RWG-12	310	1521	938	763	497	892	959	2455	6
15-Jul-05	**RWG-13**	**9167**	**1921**	**34988**	**889**	**17103**	**1201**	**38145**	3042	**211**
31-Jul-05	RWG-14	8781	257	4478	170	3128	649	19747	1127	75
15-Aug-05	RWG-15	5613	251	2800	210	2475	637	12380	1128	48
30-Aug-05	RWG-16	4261	263	2228	255	2283	677	9990	1070	35
16-Sep-05	RWG-17	2097	264	1100	255	1124	677	4918	1063	17
	***Max**+*	*8781*	*2858*	*4478*	*950*	*3128*	*1132*	*19747*	3544	75
	***Min**+*	*310*	*251*	*938*	*170*	*497*	*637*	*878*	1063	6
	Average+	***1919***	***1375***	***2404***	***582***	***1318***	***814***	***4747***	***2327***	***22***

+ excludes the July 15 sample

	Annual fluxes 10^4 tons yr^{-1}	**Na***	**Mg***	**Ca***	**Sr**
	Average	88	48	173	0.8
	September+	40-80	41-46	179-189	0.6-0.8
	March+	73-88	26-31	32-38	0.3-0.4

= two values represent the two measurements during the months.

In the Ganga, $^{87}Sr/^{86}Sr$ during the annual cycle varies from 0.71696 to 0.73001, significantly higher than the variation in the Yamuna (0.71522 to 0.71233).

The lower range in $^{87}Sr/^{86}Sr$ in the Yamuna is expected as it receives inputs predominantly from the Deccan and Vindhyan lithologies, both of which have less radiogenic $^{87}Sr/^{86}Sr$ and within a narrow range (chapter-3, Table-3.6). In contrast, the $^{87}Sr/^{86}Sr$ of the Ganga at Chhatnag (after confluence with Yamuna) will be governed by mixing of Sr brought from the Himalaya and the peninsular drainages. The $^{87}Sr/^{86}Sr$ values of the Yamuna waters seem to show a marginal decreasing trend during monsoon (Fig-4.18) probably due to enhanced contribution from the Vindhyan carbonates.

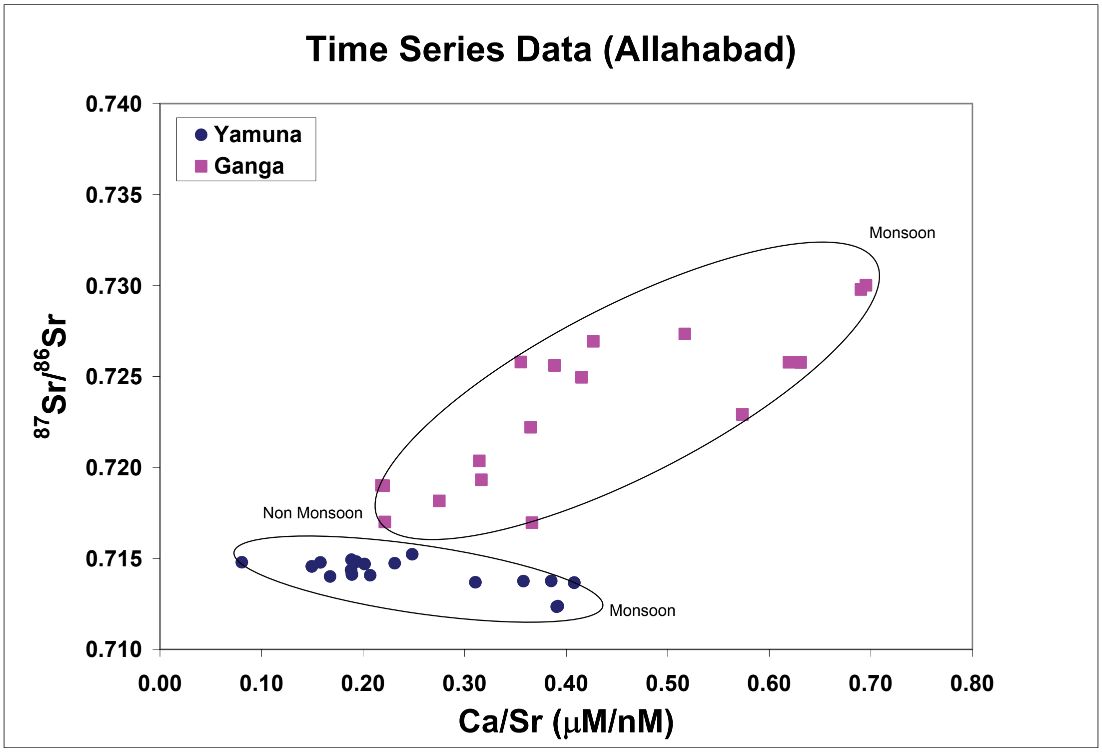


Fig-4.18: Time series (Sep.2004- Sep.2005) variation of Ca/Sr and $^{87}Sr/^{86}Sr$ in the Yamuna and Ganga River (at Allahabad after confluence). Variations in Ca/Sr and $^{87}Sr/^{86}Sr$ in the Ganga exhibit trend opposite to that of Yamuna. The trend in the Ganga can be explained in terms of mixing of two distinct sources, from the Himalaya and the Peninsular India

Considering that the Ganga sample at Chhatnag receives both Himalaya and peninsular Sr, the higher $^{87}Sr/^{86}Sr$ during monsoon is probably a result of enhanced Sr contribution from the Himalayan drainage. Sampling of the Ganga before its confluence with the Yamuna is needed to confirm this hypothesis.

4.9 Summary

Elemental and Chemical erosion rates in the plain and peninsular sub-basins of the Ganga drainage have been determined from the major ion chemistry and Sr isotope systematics of the Ganga and its tributaries. These rates in general are 2-4 times lower than those in the Himalayan sub-basin of the Ganga, mainly due to the lower run off in the peninsular and plain sub-basins and the endoreic nature of their drainages. The fluxes of various major cations and Sr from the plain and peninsular sub-basins, however, are comparable to those from the Himalayan sub-basin as their aerial coverage is a few times that of the Himalayan sub-basin. Among the major ions, Na is unique with high concentration in some of the Ganga tributaries draining the plain and peninsular sub-basins, contributing to its high flux and erosion rate from these regions. This property of Na is due to its release from various sodium salts formed in the endoreic river basins during wetting-drying cycles. Such inputs of sodium to rivers in the Ganga plain and peninsular basins restrict its application as a proxy of silicate weathering in their basins and that of the Ganga downstream of Kanpur. The results also bring out the importance of rivers draining the Ganga plain and peninsular basin as a major source of Na, Mg, Ca and Sr to the Ganga. Budget calculations show that the plain and peninsular regions together account for most of Na and 40% to 80 % of the annual flux of Mg, Ca and Sr of the Ganga at its outflow (Rajmahal). This input, therefore needs to be accounted for while estimating the chemical weathering rates of the Ganga basin in the Himalaya, based on major ion chemistry of the Ganga downstream of Kanpur.

^{87}Sr/^{86}Sr and Ca/Sr of the Ganga head waters and its Himalayan tributaries in plain were used to estimate the precipitation of $CaCO_3$ from river waters. This study is based on a two end member mixing model, carbonate and silicate rocks supplying Ca, Sr and Sr isotopes to the river. Results show that about two thirds of the Ca is removed by precipitation from the Ghaghra and the Gandak, the tributaries of the Ganga. Such precipitation of carbonates in the

Ganga plain can be an important mechanism for the formation of ‘Kankar’ carbonates. The Bhagirathi and the Kosi do not seem to be affected by such precipitation loss of Ca. Time series (biweekly) water sampling of the Yamuna and the Ganga river show that chemical erosion of different elements are season dependent and vary over the year attributable to differences in weathering kinetics of different lithologies in the basin.

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 (%)								µg 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).

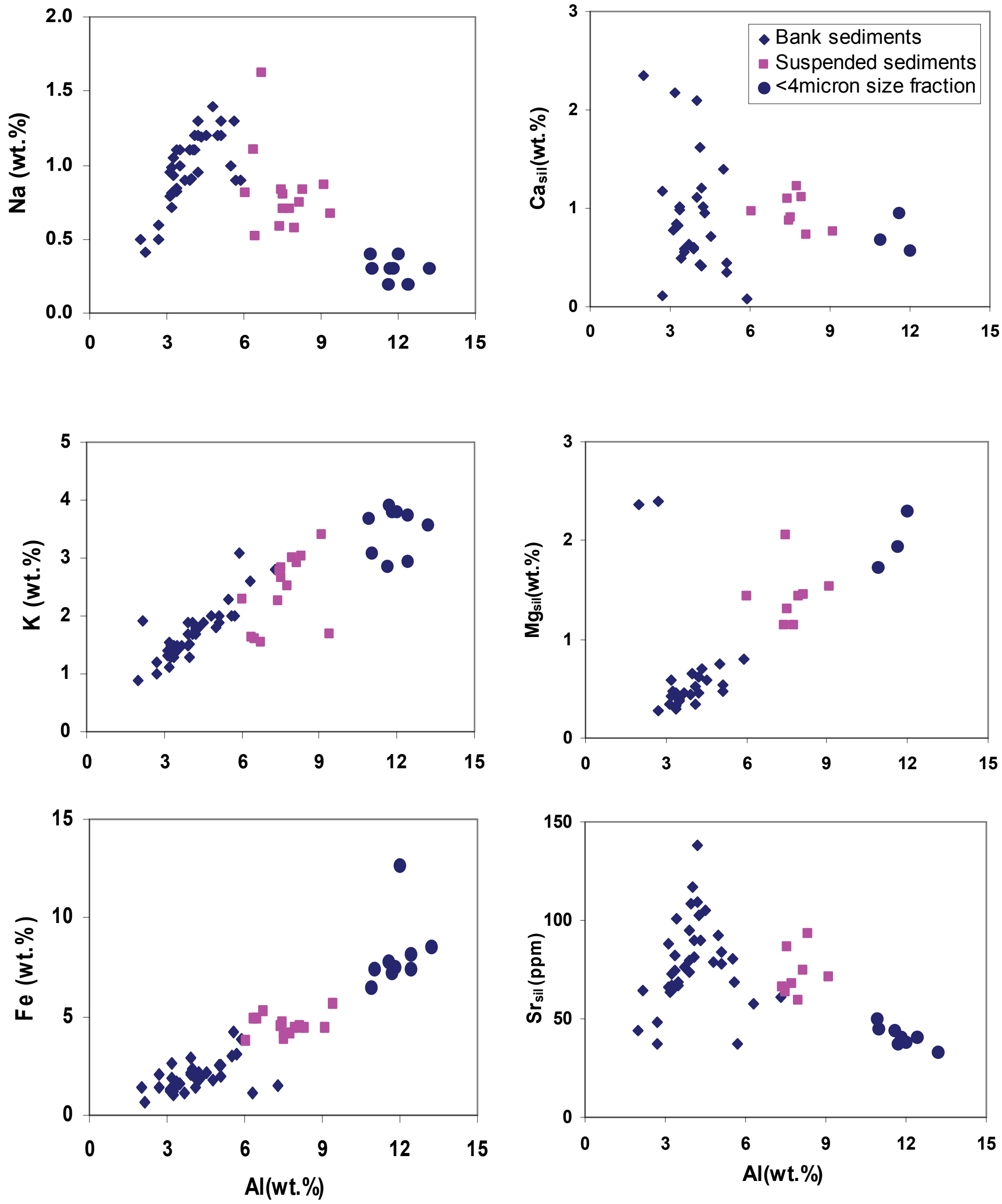


Fig-5.1: Scatter plots of Na, K , Fe, Ca$_{sil}$, and Mg$_{sil}$ wt (%) and Sr$_{sil}$ (ppm) abundances vs Al (wt %) in bank sediments, suspended load and <4μm of bank sediments. The subscript sil represents silicate component of the sediments.

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.

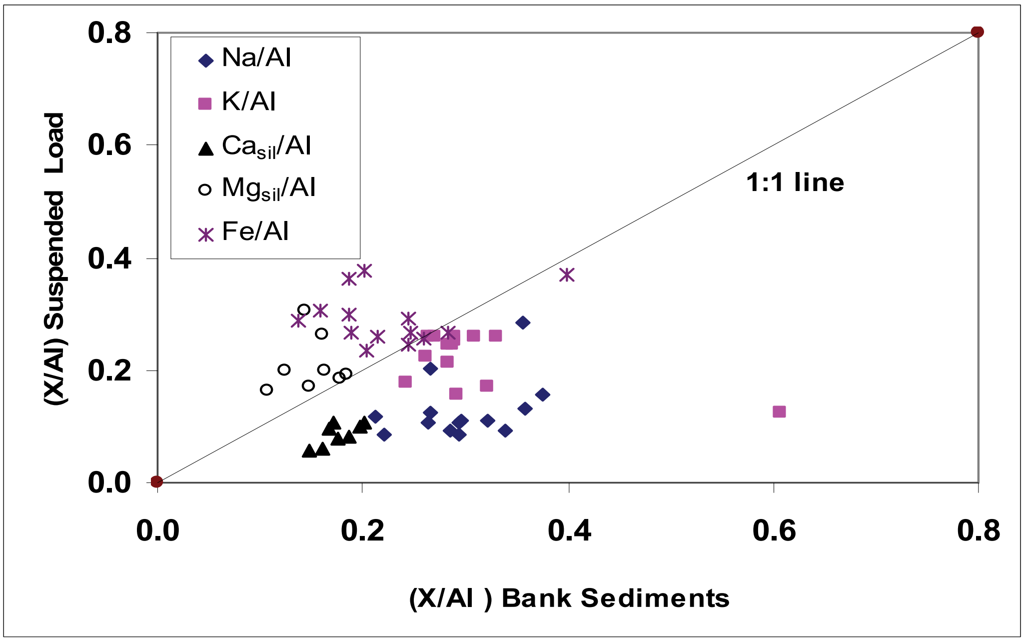


Fig-5.2: Element/Al ratios in bank and suspended sediments. Subscript sil represents carbonate corrected abundance. Na, K and Ca_{sil} show a clear depletion in suspended sediments relative to bank sediments. In contrast, ratios of Fe and Mg_{sil} with Al seem to indicate enrichment in suspended load.

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.

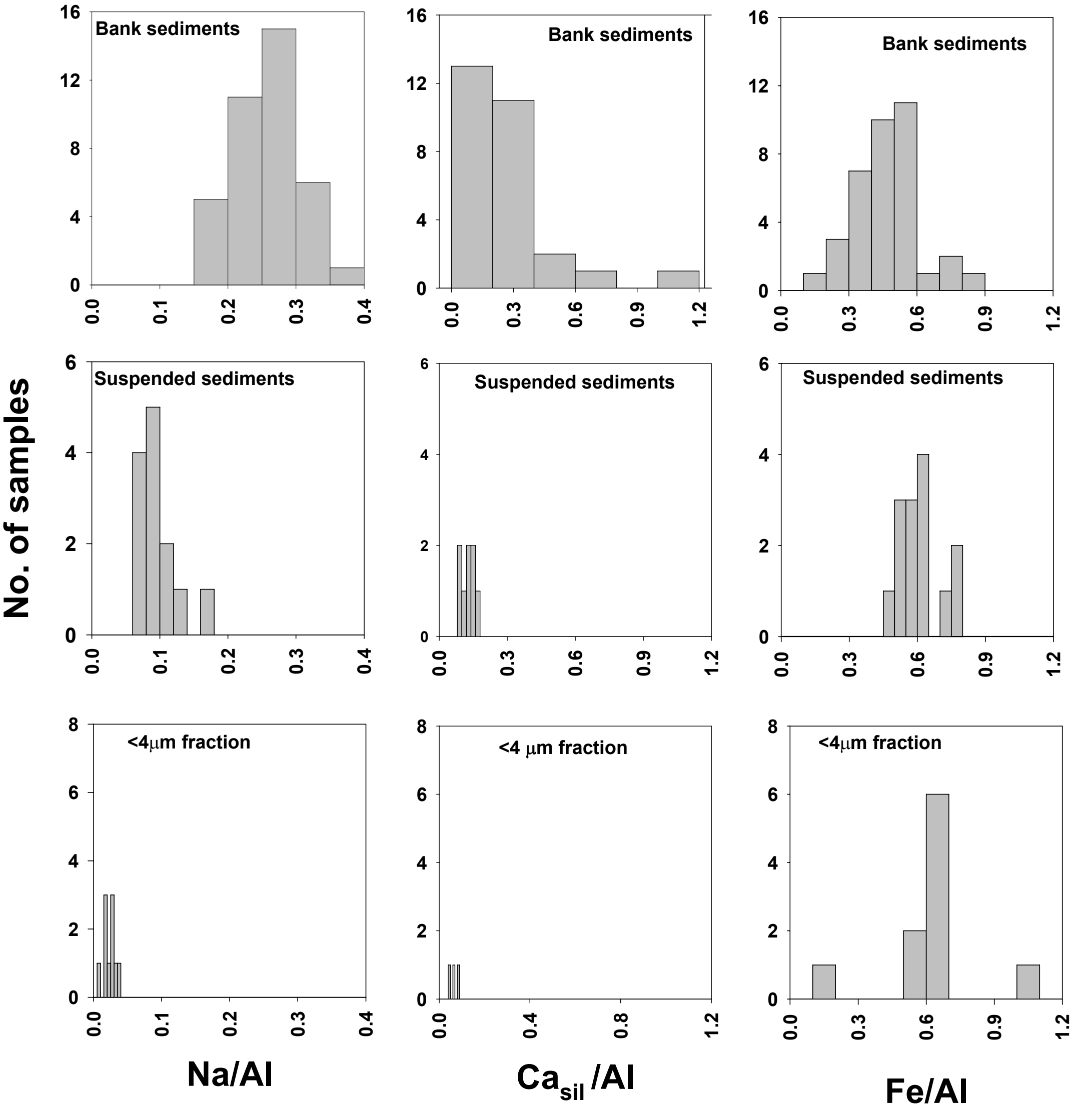


Fig-5.3: Frequency distribution of (element/Al) ratios in the Ganga sediments. Ca_{sil} is silicate derived Ca. A systematic decrease in Na/Al and Ca/Al from bank sediments to suspended sediments to <4μm bank sediments is clearly evident. The Fe/Al ratio does not seem to show any significant trend.

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.

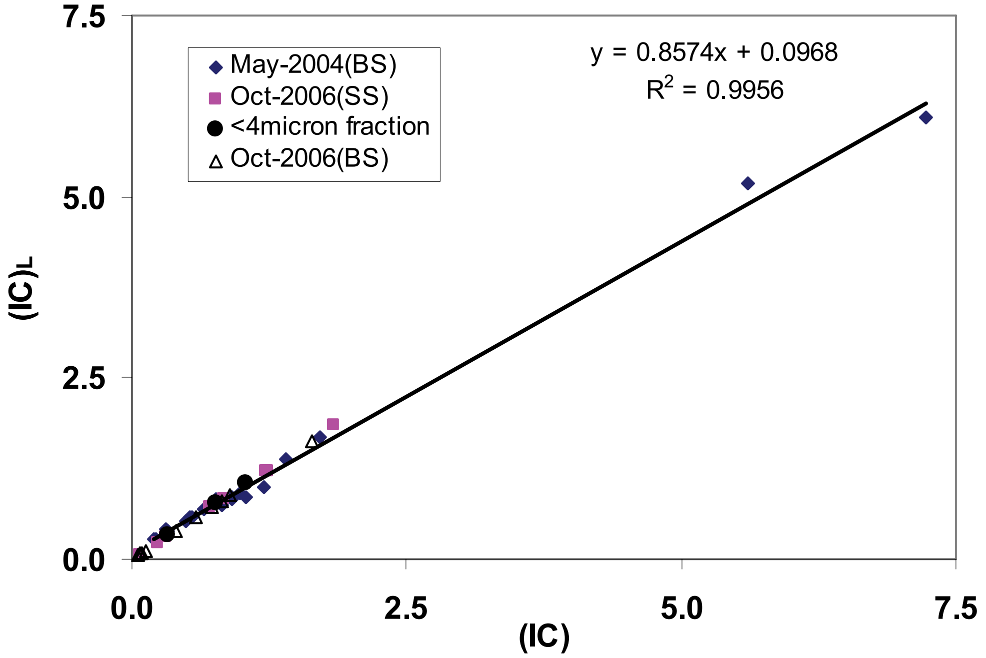


Fig-5.4: Scatter diagram of coulometer measured (IC) vs calculated (IC)$_L$ based on Ca and Mg in mild acid leach.

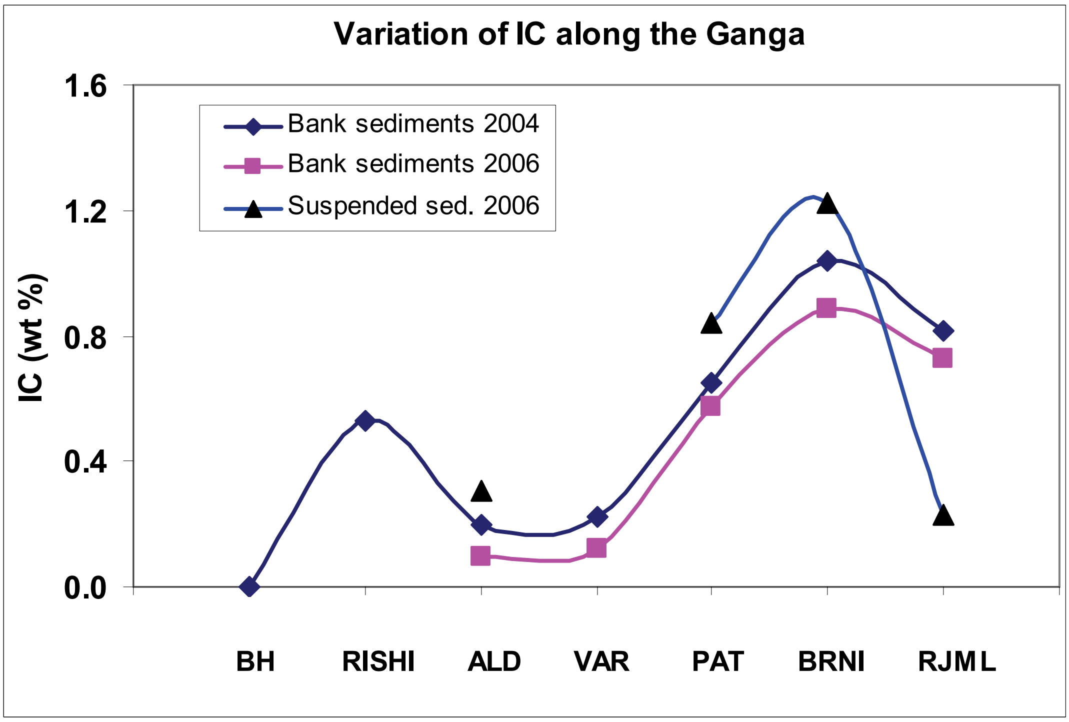


Fig-5.5: Variation of IC along the Ganga mainstream from its source to its outflow.

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:

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

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 $Na_{sil} = (Na_r-Cl_r)$. 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.

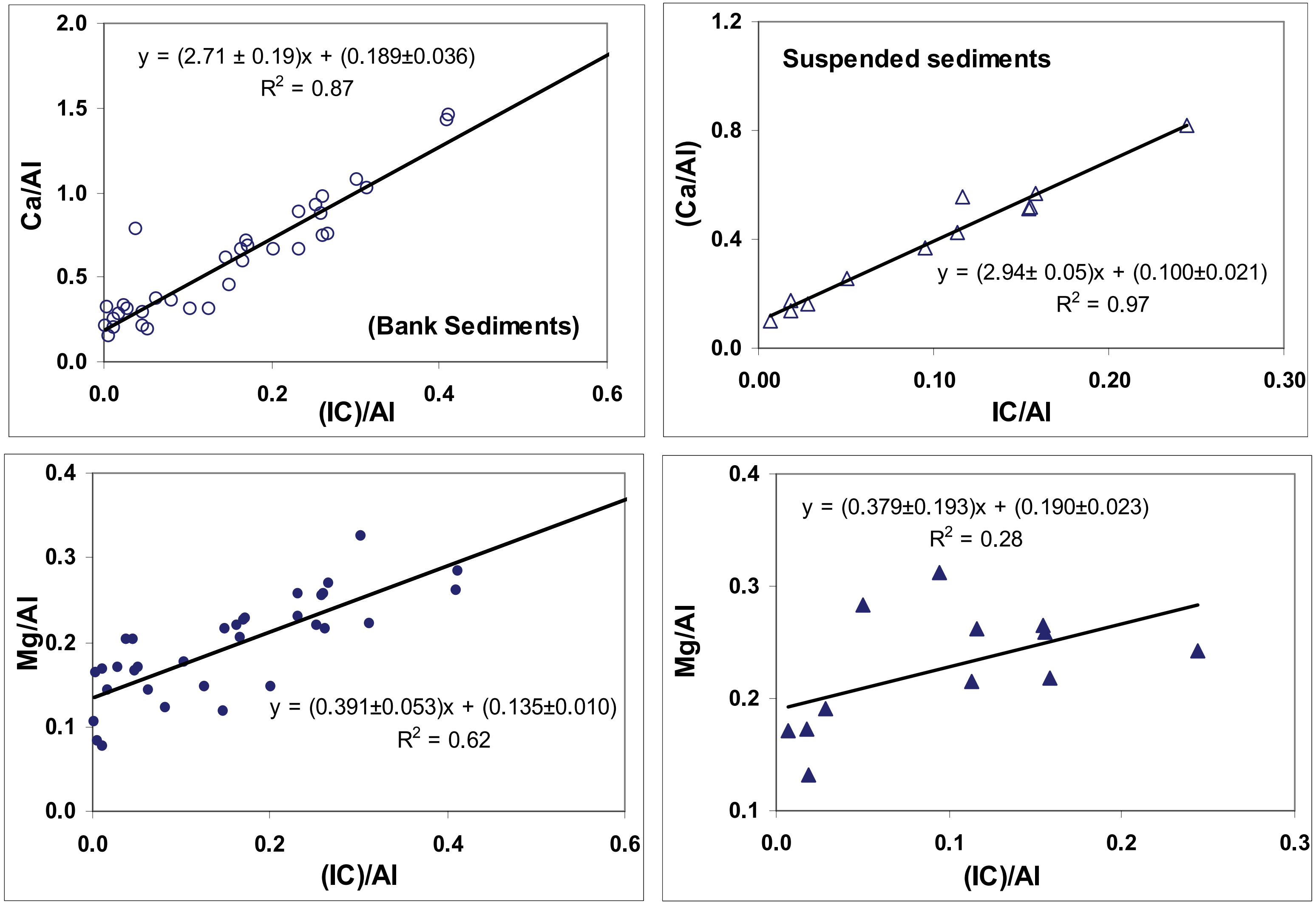


Fig-5.6: Scatter plots of Ca/Al and Mg/Al with (IC/Al) in the Ganga bank and suspended sediments (all in wt%). The intercept represents the elemental ratios in the silicate component. (Ca/Al) data show a much better fit with (IC/Al).

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.

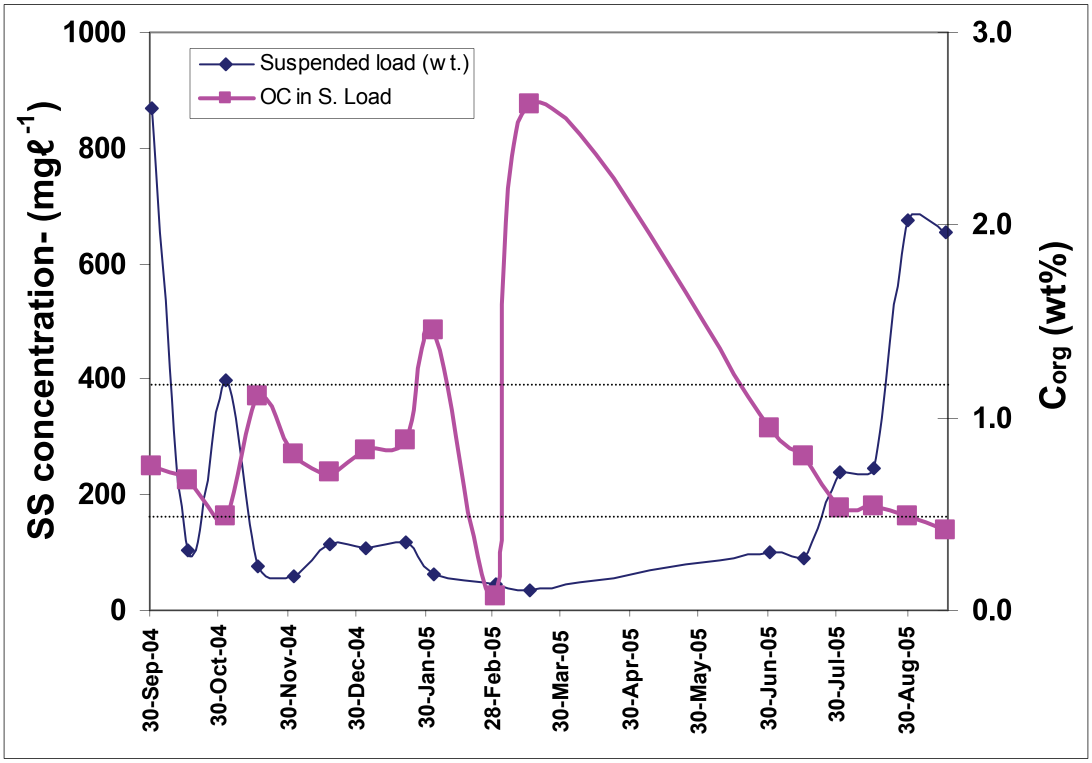


Fig-5.7: Temporal variation of suspended load (mg ℓ^{-1}) and organic carbon content (wt%) in the Ganga mainstream at Allahabad. The data though show a large range in organic carbon content of the suspended load, most of the samples have C_{org} in the range of 0.5 wt% to 1.2 wt% (dotted lines).

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).

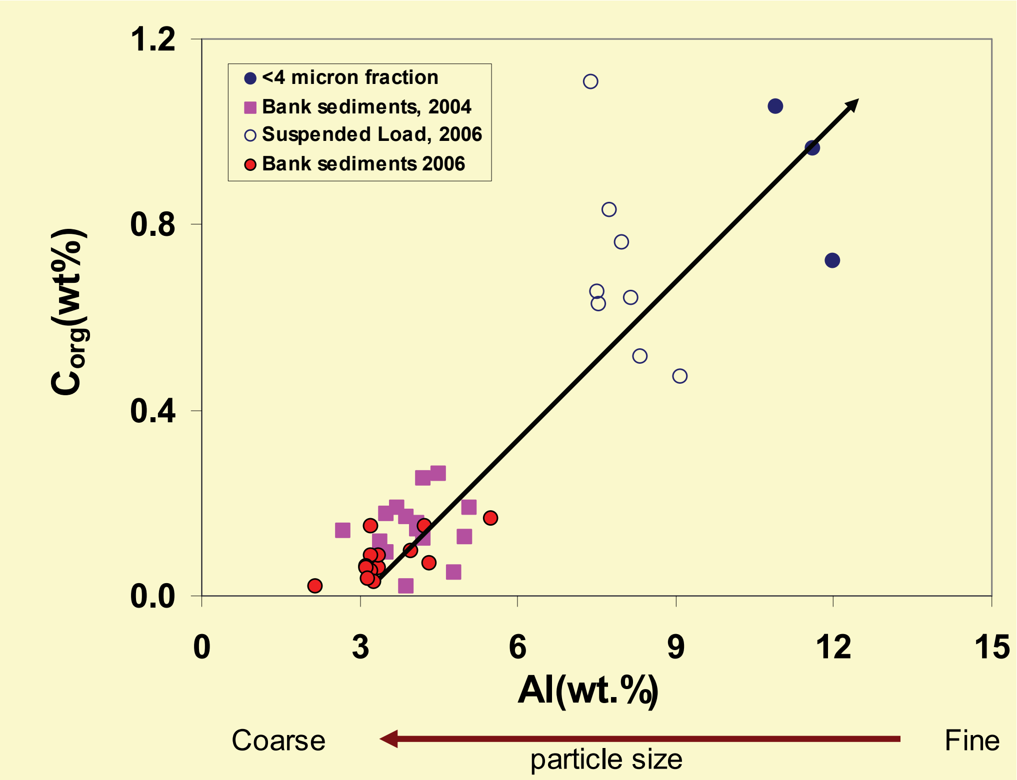


Fig-5.8: Variation of C_{org} with Al in different components of the Ganga river sediments. The plot shows that organic carbon content increases with Al, (i.e. decreasing particle size). A few samples which have C_{org} > 1.2% are not plotted (Table-5.1)

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.

Chapter- 6

Synthesis and Future Perspectives

The study described in this thesis is an investigation on the chemical and physical erosion process in the Ganga basin on different spatial and temporal scales. These sub-basins include the Himalayan, the plain and the peninsular drainages of the Ganga basin. Physical erosion processes have been studied on spatial scales of individual river basins of the Ganga system. The goals were to quantify the supply of sediments from different litho-units of the Ganga drainage to the Ganga plain and to determine variability in physical erosion rates among the various river basins and its causes. These studies have direct relevance of regional tectonics and geomorphology. Chemical erosion studies have been made on a wider spatial scale, the three sub-basins of the Ganga drainage, the Himalaya, the Gangetic plain and peninsular basins. The focus of these studies has been to quantify the chemical erosion rates in these sub-basins and to assess the role of the Gangetic plain and peninsular basins in contributing to the chemistry of mainstream Ganga and its implications to determination of silicate erosion rates in the Ganga basin and elemental fluxes to the Bay of Bengal. In addition, work also has been carried out as a part of the thesis to explore the application of chemical composition of particulate phases in the Ganga to derive silicate erosion rates.

The findings of this work have been integrated with those reported for another major Himalayan river basin, the Brahmaputra, to obtain a synoptic view of contemporary erosion processes in the Himalaya.

6.1 Studies on Physical Erosion in the Ganga basin.

Bank sediments from the Ganga and its major tributaries in the Himalaya, the plain and peninsular basin were collected and analyzed for their major elemental composition and Sr, Nd and isotope systematics ($^{87}Sr/^{86}Sr$ and ε_{Nd}). These data, in conjunction with those available in the literature for the source rocks from the Himalaya, Deccan and peninsular sub-basins have been used to quantify major lithounits supplying sediments to the Ganga plain and relative contribution of major tributaries to the sediment budget of the Ganga. The results show that the Higher Himalaya Crystallines (HHC) is the dominant source of sediments to the Ganga in the plain contributing in excess of two thirds of the total sediments. This work has also brought out the minor role of peninsular rivers in the supply of sediments to the Ganga at its out flow. Among the sub-basins of the Ganga, Gandak dominates the sediment budget contributing about half of the sediments at Rajmahal near the Ganga outflow. The present day physical erosion rates among the Himalayan sub-basins of the Ganga vary between 0.5±0.25 to 6±3 mm yr^{-1} with the highest value for the Gandak basin. The intense erosion rates over the Gandak basin is attributed to combined effects of intense rainfall in its head waters and high relief. Results obtained on the erosion rates from this study along with those available in literature for the Brahmaputra and the Indus show that within the HH, there are “hotspots” of very rapid physical erosion, with rates varying from 6 to 14 mm yr^{-1} compared to typical rates of 1-2 mm yr^{-1}. These regions are the gorges of the Brahmaputra (Eastern syntaxis), the Indus (Western syntaxis) and the Gandak. These regions undergo mechanical erosion quite disproportionate to their aerial coverage and contribute ~8% of global riverine sediment flux to the oceans.

6.2 Studies of Chemical erosion in the Ganga river system:

The emphasis of the work on this topic was to determine (i) chemical erosion rates in the Gangetic plain and peninsular sub-basins of the Ganga drainage and their impact on the water chemistry of the Ganga and material transfer to the Bay of Bengal and (ii) silicate erosion rates in the Himalayan tributaries of the Ganga and their Ca and Sr budgets. These goals were achieved through measurements of major ions, Sr and $^{87}Sr/^{86}Sr$ in various rivers the Ganga system draining through Himalaya, the Gangetic plain and peninsular basin. The results show that sum of major cation erosion rates, a measure of chemical erosion rates of the basins, on average is ~2 times higher in the Himalayan sub-basin of the Ganga compared to that in its plain and peninsular sub-basins. The Ganga plain and the peninsular drainages, however contribute significantly to the major ion and Sr budgets of the Ganga at its outflow

(Rajmahal) because of their large aerial coverage ~80% of the Ganga basin. For example, the Yamuna supplies most of Na and about half of Mg and Sr and ^{87}Sr to the Ganga at its outflow. The results bring out the dominant role of the plain and peninsular sub-basins of the Ganga in determining the elemental budgets of the mainstream Ganga. The study also shows that the Gomti and the Yamuna draining the plain and peninsular sub-basins of the Ganga are characterized by high Na erosion as a result of solution of sodium salts from alkaline and saline soils in their drainages. The supply of Na from these soils can contribute to uncertainties in the estimation of silicate Na component in these rivers and hence to the application of Na as an index of silicate erosion in their basins and therefore in the Ganga downstream of Kanpur.

The role of calcite precipitation in determining Ca and Sr budgets of the Ganga system river has been a topic of study among geochemists. An attempt to quantify the magnitude of this process in the Ganga headwaters and its Himalayan tributaries was made through measurements of ^{87}Sr/^{86}Sr and Ca/Sr in them and using a two end member mixing model for carbonate and silicate rocks of the Himalaya. Results show that about three fourths of Ca is removed from the Ghaghra and the Gandak waters by precipitation whereas in the headwaters of the Ganga and the Kosi, there is no measurable loss of Ca via precipitation. Such precipitation of carbonates in the Ganga plain may be an important mechanism for the formation of ‘Kankar’ which occur widely in the region. Further, the precipitation of calcite would lead to underestimation of Sr contribution from carbonates, calculated based on dissolved Ca abundance in rivers.

6.3 Studies on Sediment Geochemistry of the Ganga Basin

Measurements of chemical composition of bank sediments, their fine fraction and suspended matter from the Ganga system rivers were carried out to assess the intensities of chemical erosion these sediments have undergone and their utility to estimate of silicate weathering rates in the basin. Comparison of chemical index of alteration (CIA/CIA*) a measure of the intensity of chemical erosion of these sediments relative to that of source rocks (granites/gneisses) of Higher and Lesser Himalaya demonstrate that the bank sediments of the Ganga and its tributaries have not been subjected to any measurable chemical weathering. This is in contrast to the suspended matter and <4μm fraction of bank sediments which show significant chemical weathering. The loss of silicate derived elements (Na, Ca and K) from the suspended matter relative to bank sediments along with reported values for suspended load annual flux has been used to determine silicate weathering fluxes of these elements. These calculations show that for Ca and K, the sediment based fluxes overlap within errors with those based on water composition data, however for Na the sediment derived flux is about twice that estimated from water data. The cause for this discrepancy is unclear, but can be due to limited spatial and temporal coverage in sediment sampling.

Particulate organic carbon (POC) forms a minor component of the Ganga sediments. The POC flux from the Ganga ~2% of the global riverine POC supply to the world oceans. Much of POC in the Ganga is carried in its fine fraction. The sequestration rate of CO_2 by silicate weathering in the Ganga basin and the flux of organic carbon are of similar magnitude and suggest that together these two processes can be an important sink for global carbon budget. In contrast to the particulate organic carbon the flux of particulate inorganic carbon transported by the Ganga forms only ~0.3% of the depositional flux of inorganic carbon in the Bay of Bengal

6.4 Future Perspectives

Research carried out as a part of this thesis has addressed to details of physical and chemical erosion processes in the central Himalaya and its regional and global implications. There are, however, some areas related to this thesis research which need further work. These include

(i) This work demonstrated the importance of the Gandak basin as a “hotspot” for physical erosion. The results though showed that the physical erosion rate in the Gandak basin is much higher than that in other sub-basins of the Ganga, there is a need to better constrain the erosion rate estimates by reducing uncertainties. More detailed sampling, both spatially and temporally of both bank and suspended sediments and analyses of their chemical and isotopic composition are needed to obtain more precise estimates of spatial variability in physical erosion of the Ganga basin.

(ii) The measurements of the Sr and Nd isotopes made in this study showed that the isotope composition of sediments from the Ganga mainstream and some of its tributaries (e.g. the Ghaghra) overlap within errors. This limits the application of these isotope systems to estimate the sediment contribution from such tributaries to the Ganga plain. In such cases it would be worthwhile to explore the applications of other isotope systems (Os, Hf) to determine sediment contribution.

(iii) The role of saline/alkaline soils as an important source of Na to the Ganga in the plain is born out from this study. Further work related to the nature (in terms of chemical composition) and fluxes from this source is needed to better understand and quantify its impact on the application of Na as a proxy of silicate weathering in the Ganga basin.

(iv) It is shown that silicate cation erosion rates can be derived based on chemical composition of suspended matter and bank sediments. However, to understand the factors contributing to discrepancy in the erosion estimates for Na based on sediment and water data need further work. Studies on the role of suspended matter input from peninsular sources, spatial and temporal variations in chemistry of suspended matter, bank sediments and river water at the Ganga outflow need to be conducted to resolve this issue. Once the cause of discrepancy is sorted out, chemical composition of sediment cores can be used to obtain paleosilicate erosion rates.

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