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GEOCHEMISTRY OF THE GANGES RIVER BASIN

Dissertation submitted to the Jawaharlal Nehru University
in partial fulfilment of the requirements for the
award of the Degree of
MASTER OF PHILOSOPHY

109p + tables

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1982

CERTIFICATE

This is to certify that this dissertation entitled GEOCHEMISTRY OF THE GANGES RIVER BASIN is the work carried out by Mr. Nazar Abbas at the School of Environmental Sciences, Jawaharlal Nehru University, New Delhi.

This work has not been submitted in part or full for any degree or diploma of any other university.

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ACKNOWLEDGEMENT

I express my sincere gratitude to Dr. V. Subramanian, Associate Professor, School of Environmental Sciences, for his guidance during my research work. Special mention is made for S. Balakrishnan, Talat Ahmad, K. Bheemlingeshwar and Dipankar Sur of School of Environmental Sciences, and M.I.A. Beg from I.I.T., Delhi for their cooperation. I thank to all my friends who were source of inspiration while carrying out this work.

During the tenure of this work, I was financed by a Junior Research Fellowship from J.N.U.

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CHAPTER I

INTRODUCTION

In recent years, a great deal of attention is given to the detail study of small and big rivers, taking various aspects into consideration. Apart from the pollution aspect, the study of geochemical processes operating in the river basins and computation of mass-transfer from land to ocean are other important aspects of river basin studies. Various workers are engaged in this field of investigation. Alekin and Brazhnikova,(1960) have done such work in the Soviet Union. In the United States, Gibbs (1967, 1970), Livingstone (1963) and Grove (1972) have worked in this field. Until the publication of Martin and Meybeck (1979), the literature review on the chemical composition of surface water published by Livingstone (1963) was considered to be the most complete set of data on big rivers.

Martin and Meybeck (1979), based on literature review and the analysis of more than 40 elements in the Amazon, Congo, Ganges, Magdalena, Mekong, Parana and Orinoco rivers covering whole spectrum of morpho-climatic features, have published mass balance studies for various elements present in the river particulate matter. In order to study weathering on a global scale the total observed elemental flux (dissolved+ particulate) have been estimated and compared with the theoretical values. The discrepancies observed, have been attempted to explain by hypotheses involving either the natural origin (volcanic dust, marine-aerosols, geochemical fractionation) or the artificial origin (World wide pollution), etc. They have also shown the influence of river inputs on the composition of marine sediments.

Gibbs (1967) has done extensive work on Amazon River Basin and concluded that increased-relief physical weathering dominates in Andean environment, which controls the geochemistry of Amazon River. Eighty six per cent of the total dissolved salts discharged by Amazon is supplied from the 12 per cent of the total area of the basin comprising mountaneous environment type. Eighty two per cent of the total suspended solids discharged by the Amazon was supplied from mountaneous environment type. He has also pointed out the control of relief and rock type on the mineralogy of suspended sediment.

According to Gibbs (1967) increased relief physical weathering controlled the percentages of quartz, plagioclase, K-felspar, mica, chlorite and amphibole and the percentage of calcic rock in the upper portion of tributary basins controlled montmorillonite concentration while the percentages of kaolinite and gibbsite is controlled by a combination of low relief-chemical weathering and percentages of igneous and metamorphic rocks.

Carbonnel and Meybeck (1975) concluded after their study on water quality of the Mekong River, that chemical quality of the Mekong is highly variable (total ion content ranged from 60 to 190 ppm). As usual concentration decreases with increasing discharge coming from flooded tributaries. The total mineral transport to the ocean is estimated to 59.5 x 10^6 tons/year. On the contrary to the Amazon in which most of the dissolved transport comes from high mountaneous environment, the Mekong River gets the major portion of dissolved load from lower basin. This region, much exposed to rain has average dissolved transport of 75 tons/km^2/year inspite of its mid-altitude relief. This rate, three times the world average is much comparable to the Ganga one but it is half the Brahmaputra one.

Walling and Kleo (1979) attempted to study sediment yield of rivers of the areas of low precipitation on a global scale. They concluded that there is no clear cut evidence of existence of higher sediment yield or increased variability of annual yields in the river draining areas of low precipitation. Precipitation magnitude according to them is only one of the many controls of sediment yield and other factors such as climatic seasonality, relief, basin lithology and extent of human activity combine to produce a global pattern which is considerably more complex than suggested by some workers.

Grove (1972) has studied the sediment and chemical load of west African river: the Senegal, Niger, Benue and Shariu.

Gibbs (1970) discussed the mechanisms that control the world water chemistry. He cites three main mechanisms - atmospheric precipitation, rock dominance and evaporation crystallisation process - as the major factors influencing the composition of dissolved solids of world water.

In India, the study of river geochemistry is very recent. Various workers have studied some aspects of river geochemistry. The important and worth mentioning are Handa (1972), Raymahashaya (1970), Subramanian (1976, 1979, 1980, 1982), Subramanian and Dalavi (1978), Bikshamaiah (1980). Some important literatures on estuary and deltaic region in India have come from Naidu (1966), Siddique (1967), Mallick (1976) and Borole et al. (1977).

Subramanian and Dalavi (1978) have discussed the physical and chemical erosion of some Himalayan rivers and calculated the rate of erosion for these rivers. According to their study, Asia contributes approximately three fourth (1599×10^{10} Kg/yr) of all mass transfer and Indian continent alone constituting a mere 7% area of continental earth, contributes nearly 13% of the mass transfer. The denudation rate, 710 tons/Km^2/year, for India is highest in the world according to them. They have also studied the mineral stability in silicate system.

Subramanian (1978) has calculated chemical, sediment and total load carried by major river basins in India. Based on erosion rate he calculated that a period of five million year would be required to reduce the continent to base level. If it is so, then Bay of Bengal being the principal recipient of the mass will flood the continent before the time to reduce the sea level is reached.

Bikshamaiah and Subramanian (1980) have studied in detail the chemical quality of water, rate of erosion and factors controlling erosion in Godavari River Basin.

While working on the Krishna River Basin, Subramanian (1982) concluded that the Krishna River Basin is eroded at a rate of 4000 kg/Km^2/year and that in 12 million years, the basin will be reduced to mean sea level. He also observed a high rate of erosion in smaller sub-basins than the larger one.

Subramanian (1979) has studied in detail the chemical and suspended characteristics of the rivers of India. He also attempted to predict the possible mineral assemblage present in equilibrium with the Ganga River, kaolinite and dolomite are possible silicate and carbonate respectively.

Based on the study of mineralogy of suspended sediments of various rivers of India draining into adjoining sea, Subramanian (1980) concluded that kaolinite, illite and chlorite are carried in suspension particulate of the Ganga-Brahmaputra while the southern rivers carry high amount of montmorillonite and small amount of mixed layer clays. Narmada and Tapti contribute abundant chlorite, illite and kaolinite with minor amount of montmorillonite.

Naidu (1966) has done studies on the delta region of the Godavari River and found mineralogical differences between freshwater and estuarine-water sediment (Freshwater - Kaolinite 36-48%; illite 17%, (Na + Ca) montmorillonite 18-36%; salt-water-Kaolinite 14-40%; illite 18-37% ; chlorite upto 20%; Na-montmorillonite 20-46%; estuary mouth - kaolinite 15%; illite 20%; Na-montmorillonite 45%; chlorite 20%).

Siddique (1967) reported illite, kaolinite and some montmorillonite from the Bay of Bengal sediments. Mallick (1976) has studied the mineralogy of the sediment in the Ganga Cone of the Bay of Bengal and observed illite and kaolinite in the mouth of the Ganga-Brahmaputra with chlorite being abundant in individual samples. Borole et al. (1977) have studied some chemical aspects of sediment in suspension in estuaries of the Narmada, Tapti, Mahanadi and Godavari.

Gibbs (1981) concluded, based on remote sensing, sedimentation rate on shelves and submarine fans and river sediment discharge for 22 studied rivers that the submarine fans will remain cut off from their fluvial sources until the shelves and estuaries are filled and sediment can bypass these areas. The time required to fill these shelves and estuaries range from 2600 to 3,400 for the Ganges - Brahmaputra to 1 to 1.2 million years for the Yenisi-Ob. For most river system, as the author concluded, sea level will change before shelves and estuaries are filled with sediments.

Raymahashaya (1970) has given partial analysis of the Ganga water and also calculated the rate of erosion and mentioned the factors controlling erosion for the Ganga-Brahmaputra Basin. He has taken only one station (Harding Bridge) for calculation of mass transfer and erosion rate. According to his calculations the ratio of mechanical to chemical erosion is about 7 to 1 in the Ganga and 9 to 1 in Brahmaputra while Mississippi has ratio of 2 to 1.

Handa (1972) has published analysis of the Ganga River water at Rishikesh, Rajamahal and Dakshineshwar. He has also analysed the silt samples from the Ganga River water. The study has shown downstream quality variations and mineral water equilibrium. He concluded that the Ganga water is of alkaline earth bicarbonate type. However, near Calcutta, the flux of tidal water changes its character radically.

From the above brief review, it is clear that the Ganga-River Basin is not studied well to understand the various aspects as water and sediment chemistry, erosion and mass transfer (dissolved and sediment) elemental and mineral composition of suspended matters, etc. Based on the studies of the samples collected simultaneously from the Ganga and its tributaries, extensively throughoutthe whole basin an attempt is made in this study to estimate the various aspects of erosion, quality of water, water mineral equilibria and mineralogical composition of suspended matter of the Ganga River Basin, which is one of the most important river basins of the world.

CHAPTER II

GEOCHEMISTRY OF THE RIVER BASINS

The principle of 'Uniformitarianism', first enunciated by James Hutton almost two centuries ago, is still a fundamental concept in modern Geology. Hutton taught that, "the present is key to the past". With some limitations the principle holds good to understand the geological processes operating today and to extrapolate this to understand which were responsible for the present day geology.

Weathering and erosion are important geological processes operating on the surface and in the subsurface of the earth. They contribute the important mechanism in the rock formation cycle particularly in the evolution of sedimentary rocks, and the recycling of the sedimentary process can better be understood if the present day cycle is properly studied and interpreted (Garrels and Mackenzie, 1971).

Billions of tons of sediments are being continuously eroded and deposited into the sea by World's river system. River with 1.2 thousand cubic kilometers of water accounts for only 0.0001 present in the hydrosphere (Table2.1). Rivers annually discharge 4.1 million cubic kilometer of water. With this rate the total water delineated in 33 thousand years will be equal to present day ocean capacity of 370 million cubic meter (Bikshmaiah, 1979). World river are transporting annually 20 billion tons of sediments (Holeman, 1968) and 3.5 Billion tons of dissolved material (Meybeck, 1976), into the world ocean. Discharge of the solid suspended matter to the ocean by major rivers totals about 8010 million tones annually (Emery and Milliman, 1978) with the bulk (73%) derived from eastern and southern Asia. The Hwang Ho, Yangtze, Ganges and Indus River contribute significantly more suspended sediment in far higher concentration than do other rivers. For instance, the Huang Ho which drains loess deposit in northern China has an average suspended load of 15000 mg/l as compared with less than 100 mg/l for Amazon River.

Table 2.1

Distribution of Water in Hydrosphere

Segment of Hydrosphere	Volume 10^3 km^3	Percentage of total volume.
World Ocean	1370323	93.93
Ground Water	64000	4.39
Glaciers	24000	1.69
Lakes	230	0.016
Soil Moisture	83	0.005
Atmospheric Vapour	14	0.001
River	1.2	0.0001

From: 'The World's Water', Lvovich (1973).

Geological Factors Controlling River Water Chemistry

Weathering and erosion are continuously operating on the earth crust. Weathering is a process which is essentially breaking up of rocks by physical processes and decomposition by chemical reactions, while erosion is the removal of material from the earth crust by various agencies of erosion like river, glacier, wind, etc. The important physical processes are thawing and freezing, growth of roots, swelling of mineral due to hydration, diurnal temperature change, etc. (Krauskopf, 1979; Middleton and Blatt, 1972). The chemical processes are mainly chemical degradation of silicate minerals and the rock by various processes like dissociation, hydrolysis and oxidation.

The basic reaction in the chemical process is the reaction between silicates and carbonates and rain water. Some of the chemical reaction applicable to the weathering process are discussed below :

$$\underset{\text{K-felspar}}{4KAlSi_3O_8} + 22H_2O \longrightarrow 4K^+ + 4OH^- + \underset{\text{(Kaolinite)}}{Al_4Si_4O_{10}(OH)_8} + 8H_4SiO_4 \qquad (1)$$

$$CaCO_3 + H_2O \longrightarrow Ca^{+2} + OH^- + HCO_3^- \qquad (2)$$

$$CaMg\,(CO_3)_2 + 2H_2O \longrightarrow$$

$$Ca^{+2} + Mg^{+2} + 2OH^- + 2HCO_3^- \qquad (3)$$

In reaction (1), potash felspar reacts with pure water and gives clay mineral (Kaolinite) along with potassium and hydroxyl ion and nutral silicic acid. In reaction (2) and (3), the calcium and magnesium carbonate react with water to give rise to calcium, magnesium, hydroxyl and bicarbonate ions in the water.

But in most weathering reaction, the reaction does not proceed with pure water as it has been mentioned here. The rain water reacts with atmospheric carbondioxide and forms a weak carbonic acid which reacts with the silicates and carbonates to give rise to various cations and clay minerals.

$$H_2O + CO_2 \longrightarrow H_2CO_3 \qquad (4)$$

The limestone and dolomite are readily attacked with carbonic acid to give rise to calcium and bicarbonate ions in the water according to the following reactions -

$$CaCO_3 + H_2CO_3 \longrightarrow Ca^{+2} + 2HCO_3^- \qquad (5)$$

$$CaMg(CO_3)_2 + 2H_2CO_3 \longrightarrow Ca^{+2} + Mg^{+2} + 4HCO_3^- \qquad (6)$$

The aluminosilicates after reacting with carbonic acid form clay minerals and release various cations silica and bicarbonate in the river water. For example, albite may breakdown to form kaolinite and release sodium, bicarbonate and silica in solution.

$$\underset{\text{(Albite)}}{2NaAlSi_3O_8} + 2H_2CO_3 + 9\,H_2O =$$

$$\underset{\text{(kaolinite)}}{Al_2Si_2O_5(OH)_4} + 2\,Na^+$$

$$+ 4H_4SiO_4 + 2HCO_3^- \qquad (7)$$

Montmorillonite may be formed with a similar reaction

$$6(Na\text{-}Ca)Al_2Si_2O_8 + 6CO_2 + 18H_2O =$$

$$\underset{\text{(montmorillonite)}}{3Na_{.66}Al_{2.66}\,Si_{3.33}O_{10}(OH)_2}$$

$$+ 2Ca^+ + 2Na^+ + 6H_4SiO_4 + 6HCO_3^- \qquad (8)$$

The chemical weathering of calcite produces Ca^{+2} and HCO_3^- in ratio of 1:2 whereas, the solution of pure dolomite produces a water containing Ca^{+2}, Mg^{+2} and HCO_3^- in the ratio 1:1:4. The water resulting from reaction (7) would contain HCO_3^-, Na^+ and H_4SiO_4 in ratio 1:1:2. Thus, each molecule of CO_2 produces one HCO_3^- fromsilicates and two HCO_3^- from carbonates.

The chemical weathering of silicate minerals is very important since they constitute more than 75% of the rocks with which rain water comes in contact. These mineral include chiefly quartz, olivine, pyroxenes, amphiboles, feldspars, micas, and clay minerals. Weathering of silicate and especially aluminosilicate play important role in supplying dissolved constituents in natural water. The concentration of many constituents in natural water are controlled by equilibria involving one or more silicate minerals (discussed later).

A simple silicate mineral like olivine may react with the rain water to give rise to cations, bicarbonate ion and silica acid

$$Mg_2SiO_4 + 4CO_2 + 4H_2O \rightarrow Mg^{+2} + HCO_3^- + H_4SiO_4 \tag{9}$$

In this reaction, acid is consumed and with further reaction the water becomes more alkaline. In nature, the composition of silicates is more complex than the one mentioned. Once the cations go into solution, the silicate grain is armored by a mineral of somewhat different composition and further reaction slowes down because diffusion has to take place through the inert armor layer.

Aluminium is nearly immobile as a dissolved constituent in most natural water. Because of this, aluminosilicates weather to more aluminous solid phase by incongruent solution. The chief alteration product of the attack of acidic water to be first formed is Kaolinite (7). However, other alteration product may form depending on the composition of the primary minerals being weathered and acidity of the rain water and residence time of attacking water. These products include montmorillonite, chlorite, illite, various iron and aluminium hydrates. In this kind of reaction also (7), the acid is consumed and solution becomes progressively more alkaline, and reaction slows down. It is also because of the armoring of original aluminosilicate by kaolinite.

Apart from the parent rock material, composition of clay minerals also depends on the climate. Gibbsite which needs the continuous removal of silica to form, will develope only in the areas which are continually drained. Kaolinite is found in areas of temperature climate with moderate to heavy rainfall, Since the formation of montmorillonite requires high cations, HCO_3, pH and dissolved silica, it is expected in soils of semiarid regions.

With the progressive attack of CO_2 bearing rainwater, some constituent are removed and some are enriched in the rock. There is a rapid decrease in sodium magnesium and calcium (mobile constituents). and somewhat slower for potassium and silicon. The iron and alumina are relatively enriched in the rock.

The order of loss just mentioned is common one for the weathering of all types of rocks, but it is just by no means universal (Krauskopf, 1979). The disappearence of a particular mineral will depend upon various factors - mineral composition, rock texture, climate, drainage, amount of exposure etc.

etc. The order of loss of elements are the reflection of susceptibility of various minerals to weathering. Ordinarily mafic minerals decay more rapidly than felsic minerals (although by no means always), liberating magnesium, iron and in lesser amount calcium and alkali, iron is in large part oxidized immediately to insoluble ferric oxide, so remains with the weathered material instead of being carried off in solution. Among felspars, plagioclase weathers faster than K-felspar and calcic plagioclase faster than sodic plagioclase, thus, liberating sodium and calcium more rapidly than potassium. When cations are set free, the Al-Si-O frameworks of the original silicate minerals are in part decomposed, in part reconstructed into the framework of clay minerals, so that only a part of silicon and very little of the aluminium find their way into solution (Krauskopf, 1979).

The susceptibility of various minerals to chemical weathering is in reverse order to that of crystallization (Bowen's reaction series). Goldich (1938) who studied in detail the chemistry and mineralogy of several soil profiles gave a "mineral stability series", in which the minerals are arranged according to decreasing rate of decomposition.

Stability during Weathering	Mafic minerals	Felsic minerals
Low		
↕	Olivine	
		Ca-Plagioclase
	Pyroxene	
		Ca-Na Plagioclase
	Amphibole	Na-Ca Plagioclase
		Na- Plagioclase
	Biotite	
		K-feldspar, muscovite
High		Quarts.

The dissolved material from the weathering of rocks are not only continually incorporated into the water but are also removed by the proper balancing with the water mineral equilibria. If the initial CO_2 is high the Ca^{+2} and HCO_3^- will dissolve more but a point will reach where the activity of Ca^{+2} and HCO_3^-, will reach (solubility product of $CaCO_3$) to precipitate calcite or aragonite (shown in later section). Same way when the concentration of cations and SiO_2 increases in the water from the weathering of rocks, kaolinite is formed and dissolved silica and allumina are abstracted from the water. The sodium and potassium can be extracted from the water to give rise to montmorillonite and illite respectively.

Types of Weathering :

The dominance of one type of weathering on the other and the nature of weathering depends upon various factors like relief, rocktype, climate, vegetation, etc. In an over-simplified manner it can be said that physical weathering dominates in high relief while chemical weathering dominates in low relief environment. (Fig. 2.1). Rocktype and climate are other very important factors which control the nature of weathering. For example, in the environment of high relief, low precipitation and arid climate there will not be much of physical weathering. Of course, there will be some as it is pointed out by Thornbury (1954) that weathering proceeds even in dry climates. In the same way an

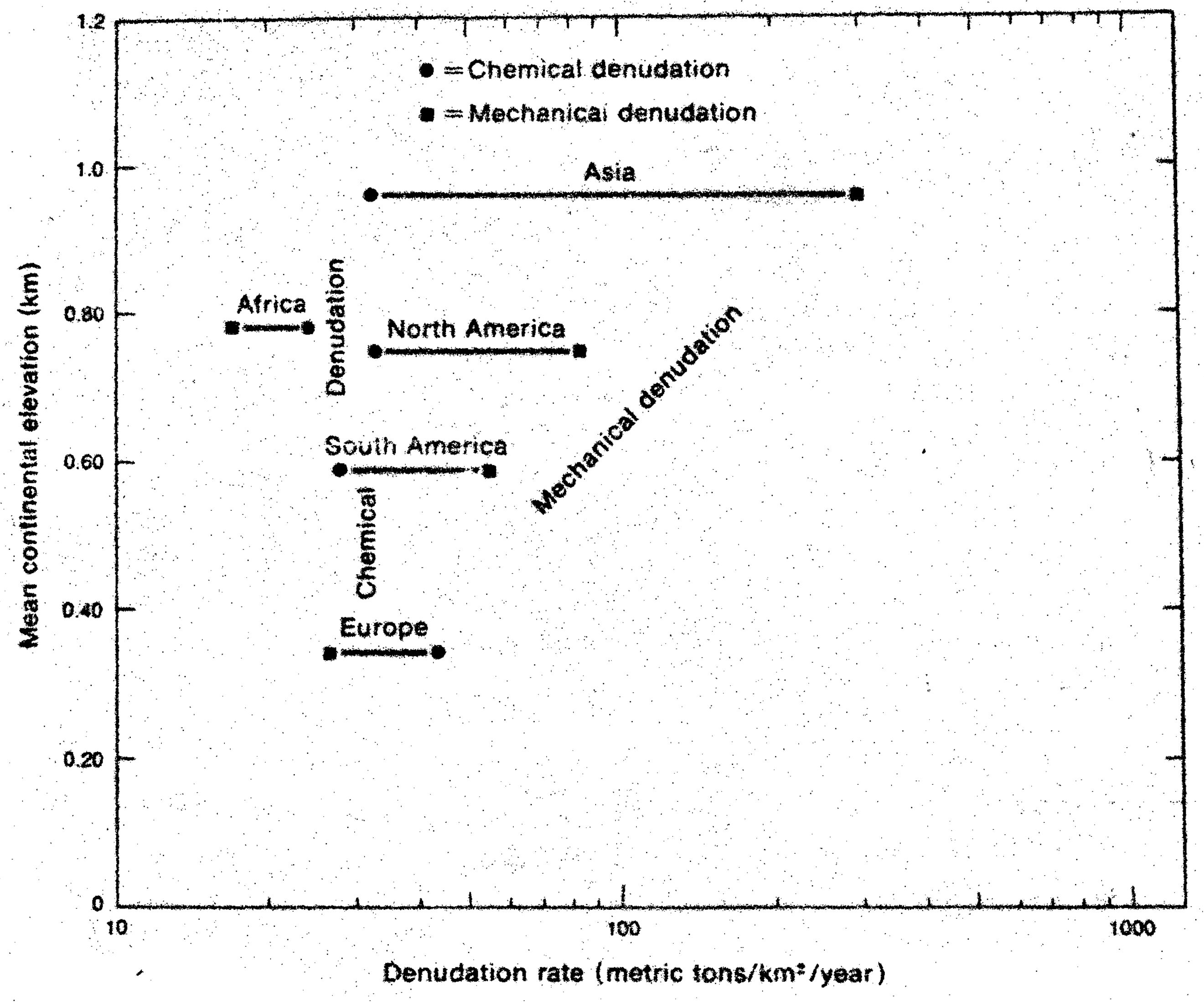

Fig. 2.1: Graph showing chemical denudation, independent of continental elevation; whereas, mechanical denudation generally increases with increasing elevation (Garrels and Mackenzie, 1971).

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area with low relief and calcic rocks will not be much weathered if there is no precipitation.

This does not mean that there is one to one ratio between the volume of water and material moved into the ocean. Specific discharge (discharge per unit area) seems to be uncorrelated with either rate of chemical or mechanical denudation, Europe with intermediate rate of specific discharge has the highest rate of chemical denudation. On the other hand, Asian stream with an intermediate specific discharge are transporting about 20 times as much solid material to the sea from each square kilometer as the streams of Africa (Tables 2.2, 2.3).

Garrels and Mackenzie (1971) pointed out that analysis of the data from individual drainage basin usually show an increase in chemical denudation with increasing elevation, but on a continental scale, this effect seems to be overwhelmed by rock type.

Most river waters are dominated by Ca^{+2} and HCO_3^-, and it is these two species that account for most of the differences in total dissolved load between the dilute waters from South America and the

Table - 2.2: Erosion rate for the Continental Earth
(Garrels and Mackenzie, 1971 (Modified by Subramanian, 1978))

Continents	Chemical Load	Sediment Load	Total Load	Chemical Rate	Sediment Rate	Total Dinudation Rate
		10^{10} Kg/year			10^4 Kg/Km^2	
Asia	149.0	1450.0	1599.0	3.2	30.24	33.4
Africa	71.0	49.0	120.0	2.4	1.63	4.03
Europe	46.0	25.0	71.0	4.2	2.27	6.47
Australia	2.0	21.0	23.0	0.2	2.10	2.30
North America	70.0	178.0	248.0	3.2	8.48	11.78
South America	55.0	110.0	165.0	2.8	5.60	8.40

Table 2.3 Specific Discharges of the Continents
(Calculated from Garrels and Mackenzie, 1971)

Continents	Area $Km^2 \times 10^6$	Discharge $m^3/sec \times 10^6$	Specific Discharge $m^3/sec/Km^2$
Asia	48	0.34	0.0070
Africa	32	0.18	0.0056
Europe	12	0.13	0.0065
Australia	8	0.03	0.0037
North America	20	0.22	0.0100
South America	22	0.08	0.0070

more concentrated one from Europe. The reciprocal relations in the Ca^{+2} and SiO_2 concentration of the most of river water is suggestive of control by rock type. Calcium is expected to be derived from limestone and evaporites and silica from weathering of silicate minerals. The 'limy' continents are more reactive than one made up of silicate mineral hence their dissolved load and chemical erosion rate is higher than the "silicious" continent. It is very well demonstrated by plotting chemical denudation rate versus $(SiO_2 + HCO_3^-)/SiO_2$ as an index of limy nature of the continent (Fig.2.2).

These factors are very intermingled and a combined interaction of all the factors give rise to a particular type of weathering or the dominance of one type of weathering on the other. Moreover, the two types of weathering can not be considered in isolation because they are somewhat interdependent. For example, the chemical action of water in granitic rocks makes the intergrain boundaries and cleavage planes much weaker which further facilitates the breaking up of the rocks easily by physical processes.

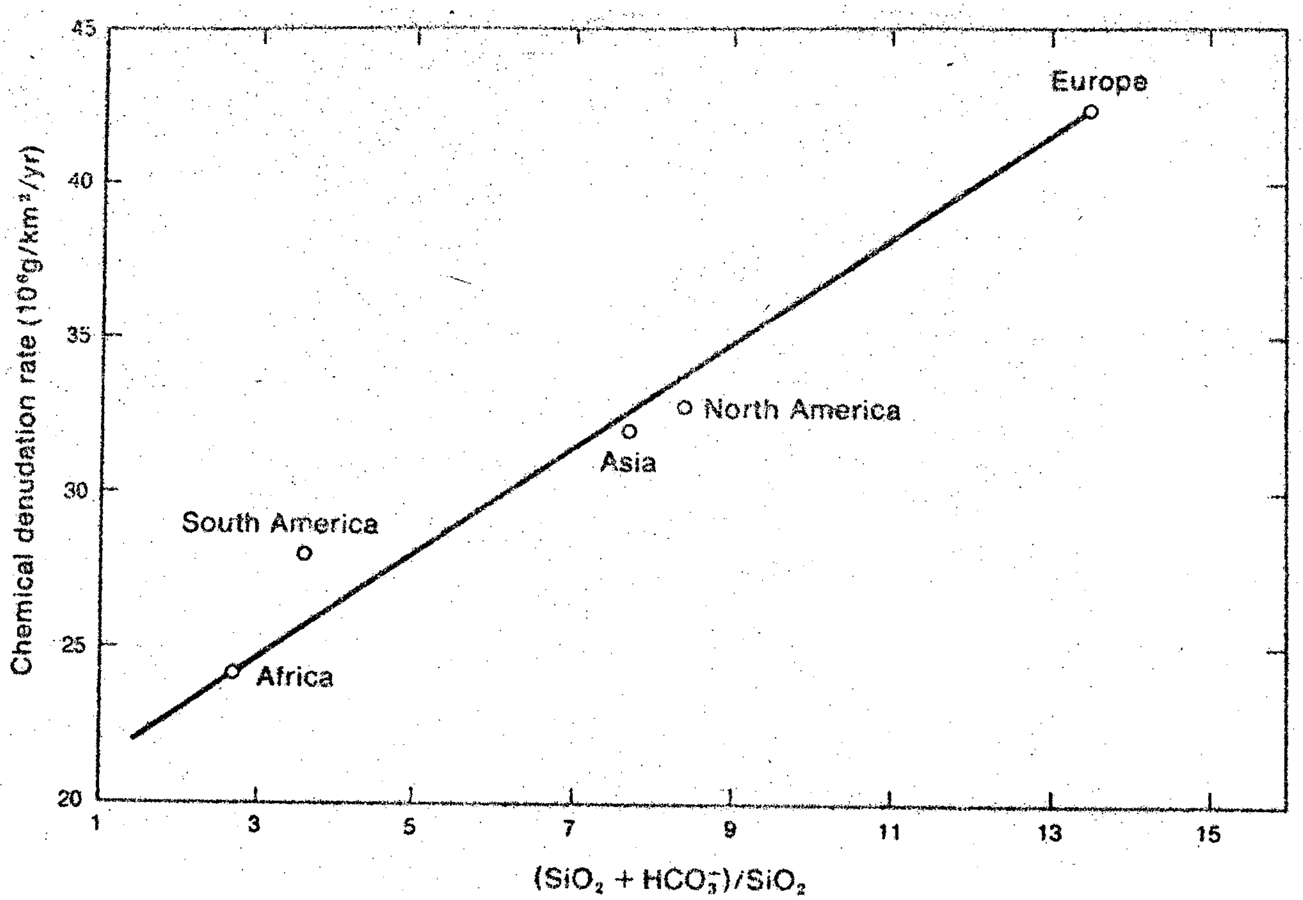

Fig. 2.2: Increase in chemical denudation rate of the continents as a function of the silica and bicarbonate content of the stream waters, indicating that denudation rate increases as the proportion of bicarbonate rocks eroded increases (Garrels and Mackenzie, 1971).

Sources of Ions in Natural Waters :

According to Harris and Adams (1966), water acquires its constituents from various sources like atmospheric fall out as dust, salt particle from sea, volcanic debris, reaction during groundwater recharge, mineral dissolution and release of solute during chemical weathering.

The carbonic acid formed by the solution of carbon dioxide and rainwater (4) may dissociate to give rise to bicarbonate ions in the water

$$H_2CO_3 \qquad HCO_3^- + H^+ \qquad (10)$$

The carbonic acid after reacting with carbonate and silicate gives rise to bicarbonate according to reactions (5), (6) and (7).

The bicarbonate can also be incorporated in the water by partial or complete decomposition of organic matter. This has been experimentally demonstrated by Berner (1971)

$$C_6H_{12}O_6 + 6O_2 = 6CO_2 + 6H_2O \qquad (11)$$

$$CO_2 + H_2O = H^+ + HCO_3^- \qquad (12)$$

As mentioned by Subramanian (1976), the bicarbonate in the water may be incorporated from the waste of petrochemical industries and coal industry.

$$2CH_2O + SO_4^{--} \quad - \quad 2CHCO_3^{-} + H_2S$$

$$2CH_2O + SO_4^{--} \quad - \quad H_2CO_3 + S + CO_2 + H_2O.$$

Sulphate in the natural water is derived from the sulphate and sulphide minerals (gypsum-pyrite), present in the rock. These minerals after reacting with the water form sulphate -

$$FeS_2 + H_2O + 3O_2 \qquad 2H_2SO_4 + Fe^{++}$$

$$CaSO_4 + H_2O \qquad CaO + H_2SO_4$$

$$H_2SO_4 \qquad 2H^{+} + SO_4^{--}$$

Apart from this, sulphate also comes from artificial sources. The fossil fuel burning release lot of SO_2 and SO_3 which after combining with the atmospheric vapours form sulphuric acid. This acidic water comes down in the form of acid rain which may attack black shales containing pyrite and marcasite to breakdown and form sulphate ions.

Sodium and chloride ions in the water are derived from weathering of rocks, halite, and recycling of sea water. Rocks containing sodic plagioclase, mica and other minerals having sodium and chlorine as their constituents give rise to sodium and chloride ions in the water. Halite (NaCl) which is present as bedded salt deposits and dispersed in other rocks gives Na and Cl ions after dissolution. The solubility of NaCl in pure water is about 6 mole/litre or about 350 g/1000 g of water at 25°C so it will be dissolved greatly before the solution is saturated. In the recycling the sea water droplets are caught in the wind from the bubbling and bursting of sea water. These droplets are evaporated and tiny solid particles are precipitated which are carried landward by turbulent wind. They are added to the surface water by rain.

Livingstone (1963) estimated that 46% of the annual river flux of sodium is atmospherically cycled. Garrels and Mackenzie (1971) estimated that 55% Cl^- in the river is derived from rocks and 45% from recycling through atmosphere.

The common sources of potassium are orthoclase, microcline, biotite, leucite, and other potassium bearing minerals and rocks like granite, syenite, arkose, mica-schist etc. Besides these, potash fertilizers also incorporate substantial amount of potash in natural water.

River Sediment :

The river sediments are the product of mechanical decomposition of the rocks in the provinance. Their chemistry and mineralogy depends upon the nature of the alteration processes operating in the basin area. The stability of the minerals present in the river depend mainly upon the Eh, pH and activity of the various species present in the water. The clastic sediment are the disintegrated rock particles. They are mainly quartz, some felspar, amphibole and some heavy minerals.

Factors like relief, rock type climate etc. control the sediment yield and the nature of sediment in the river. Gibbs (1967) concluded that relief increased physical weathering controlled the amount of quartz, plagioclase, K-felspar, mica, chlorite, amphibole and that the percentage of calcic rock in the upper portion of tributary basin controlled the amount of montmorillonite. Then a combination of low relief chemical weathering and percentage of igneous and metamorphic rocks controlled the percentage of kaolinite, gibbsite in the suspended matter of the Amazon River Basin.

Transportation of River Sediment :

(a) Mechanism of sediment movement : Two main mechanism have been invoked: the fluid drag on an exposed grain which tends to roll it over the surrounding grains, and the hydrodynamic lift force which tends to lift the grain vertically up from the bottom and project it into the fast moving part of the flow. Studies on the movement of grains by wind, using high-speed motion photography have shown that grain, do, infact rise up almost vertically from the bed and that they move in a succession of leaps by a process called as saltation.

When water is permitted to flow over a mobile bed, the discharge being gradually raised from zero, the bed particle will begin to move at a given critical boundary shear. Similarly, when flow is reduced gradually from a high discharge, the sediment particle will cease to move at a certain value of critical boundary shear.

The two values of the critical shear, namely that for the initiation of motion and that for the cessation of motion, are utilised to describe the character of the sediment. If these two shears are equal or nearly equal, the material is considered non-cohesive in nature. On the other hand, if the critical shear required to initiate motion is much larger than that required for the ceasing of sediment motion, the material is considered to be cohesive. (Rao, 1975).

(b) Transportation of Bed Load : Once the shear stress has been raised above the critical value, sediments of a given grain size will move over the bed but rate at which it will move is limited. The mode of sediment motion depends strongly on the grain size. Grains larger than sand move only by sliding and rolling (traction). Only very rapid flows are capable of moving such grains by saltation or suspension. Sand moves largely by saltation and intermittent suspension, and silt and clay move in suspension supported by fluid turbulence.

The material in the river beds are commonly coarse silt to sand or coarser. The rate of movement of bed load does depends on hydraulic conditions. These in turn are partly controlled by the rate of supply of bed material from mass-wasting. For example, a high rate of supply of coarse material at a certain point in a river valley may lead to accumulation of material until erosion downstream has steepend the slope to the degree necessary to increase the shear stress and establish an equilibrium between the rate of supply of sediment and its rate of transport by the river.

The sediment transport system is inherently a very complicated natural feed back system. As soon as transport begins, the flow begins to mold the bed into bed form, which migrate and progressively changes their form in response to changes in the flow. In turn, the rate of bed load movement depends on the nature of bed forms (Middlton and Blatt, 1972).

(c) <u>Transportation of Suspended Load</u> : When water flows in a channel with low velocity, i.e., when Reynold's number is very small (less than 2,000), the water filament glide over one another forming an orderly pattern of trajectories known as streamline. On the other hand, when velocity is high or Reynolds number is increasing beyond 2,000, the filament of the currents become completely irregular and traversed with numerous disorderly cross current and vortices, the flow becomes turbulent.

The mechanical effect of these cross current and vortices are such as to equalise the various flow parameters. This equalising action is the result of a mixing process consisting of penetration of water particle from one layer having a given velocity into another layer having a different velocity. It is the velocity fluctuation normal to the mean flow direction that are responsible for holding particles in suspension and for diffusing particles across the channel. It may be predicted, therefore, that there will be a substantial quantity of sediment held in suspension only if the strongest vertical velocity fluctuations are greater than settling velocity. Therefore, only those particles will be freely suspended that have settling velocities with magnitudes less than 8% of the mean velocity.

Rivers have almost unlimited capacity to transport clay and fine silt so the concentration of these grain size found in a river depends mainly on the rate of supply by erosion in the watershed, rather than on hydraulic conditions. Such material does not commonly occur in large quantities in the bed of the river and is described as suspension or washload.

Deposition of River Sediment :

The products of weathering after various methods of transportation, eventually reach the ocean through estuaries. The suspended silt and clays of river water are flocculated in the estuarine region due to high electrolyte content of estuary water and are deposited mainly in estuaries and continental shelves. Some clastic material may move well beyond the continental shelves and eventually settle in the bottom of the deep ocean. The clastic sedimentation is explained by Stoke's Law. There are wide variety of environment like delta, barrier islands, deep ocean water associated with turbidity current which are beyond the scope of discussion of this work.

CHAPTER III

DESCRIPTION OF THE GANGA RIVER BASIN

Description of the River

The Ganga originates from Gangotri Glacier in Uttarkashi district at an elevation of 7010 m. In the beginning the river is not known as the Ganga but there are two small rivers known as Alknanda and Bhagirathi, they join at Dev Prayag. After this confluence only the river is known as the Ganga.

The river traverses in the Himalayan mountaneous terrain for about 250 km and descends into plains at Rishikesh. The Ganga in the upper plains passes through important cities like Kanpur, Allahabad, Varanasi and then enters into Bihar in the middle region (Fig. 3.1). In the upper plain region, it receives the Ramganga Tons and Gomti River from the north and the Yamuna (which itself has got tributaries like Chambal, Betwa, Ken, etc.) from the south. In the middle region many important tributaries like Ghaghara, Gandak, Son and Kosi River join. In the lower Ganga basin, only Mahanadi joins. Later 100 km downstream from Rajamahal, the river is not known as the Ganga, but bifurcates into

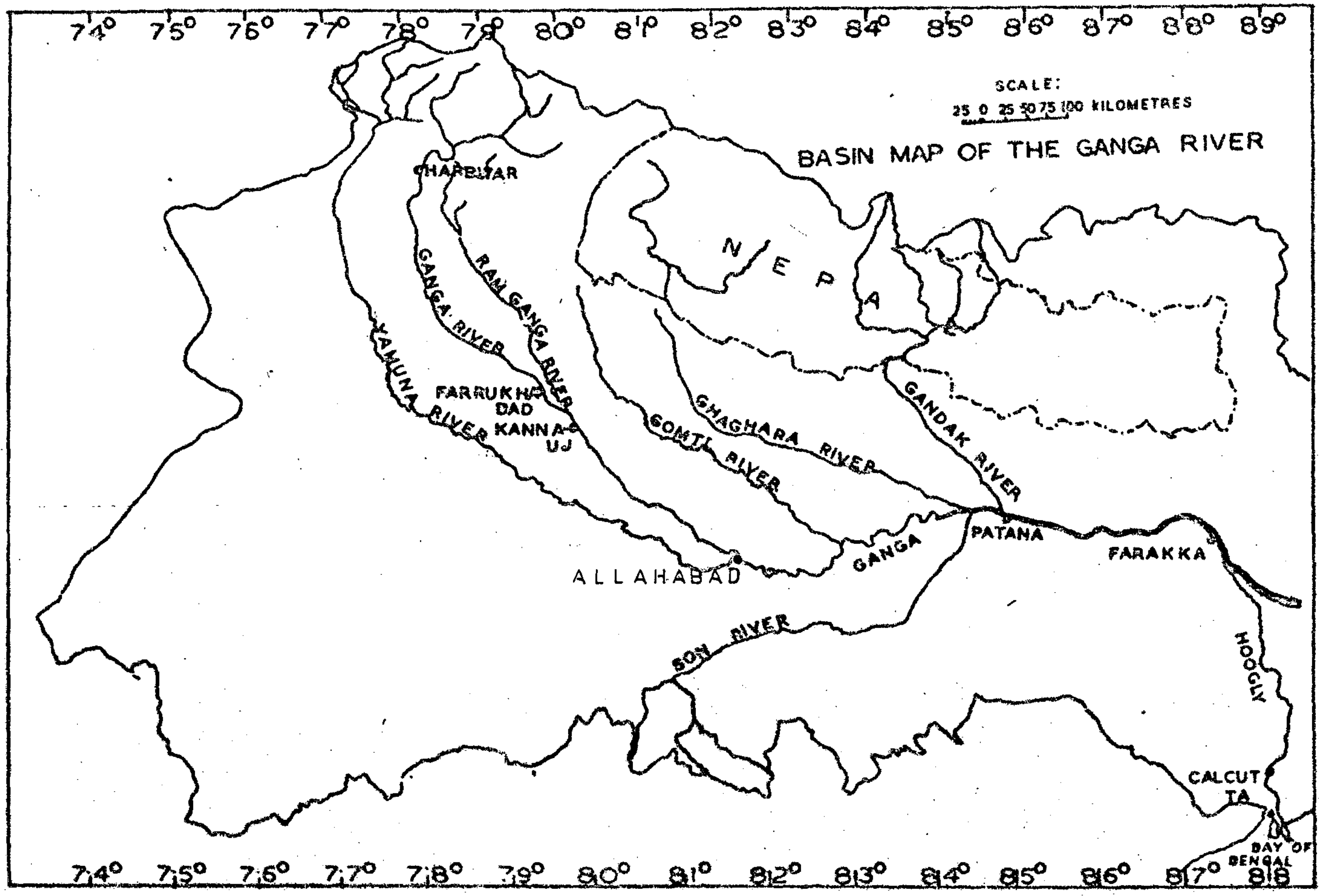

Fig. 3.1: Basin map of the Ganga River showing some sampling stations.

Bhagirathi which further downstream is known as the Hoogly draining through India and falls in Bay of Bengal and the Padma which drains into Bangladesh. The river after entering into Bangladesh joins Brahmaputra River and at the end it breaks into numbers of estuaries. After passing through the dense forests of Sunderbans, the river falls into the Bay of Bengal.

The total length of the Ganga from Gangotri to its outfall into the sea (measured along the Hoogly) is 2525 Km (Rao, 1975). Of its total length, 1,450 km is in UP, 445 km in Bihar, 520 Km in West Bengal. It forms the boundary between UP and Bihar for a length of 110 km.

On the average, the Ganga discharges 459040 million cubic meter water annually (Rao, 1975). Taking the discharge as a measure the Ganga is the fifth largest river of the world after Amazon, Kango, Mekong and Brahmputra River. In terms of sediment yield, Holeman (1968) ranked the Ganga as the second largest river of the world.

Ganga River Basin

The Ganga River Basin is bounded in the north by the Himalayas and in the south by Vindhyas. The Ganga River Basin since the beginning of history, and in particular the Ganga River, were very important. The early civilization started on the bank of this river. In the words of Jawaharlal Nehru, our late Prime Minister, 'The Ganga is above all the "River of India", which has held India's heart captive and drawn unaccounted millions to her banks since the dawn of the history. The story of the Ganga from the source to sea, from old times to new, is the story of India's civilization and culture, of great and proud cities, of the adventure of man and quest of the mind which has so occupied India's thinkers, of the richness and fulfilment of life as well as its denial and renunciation, of the ups and downs of growth and decay, of life and death' (The Discovery of India).

The basin area of the Ganga River in India is 861404 sq.km. extending between 74°N to 89°N latitude and 31°30'E to 22°E longitude. The basin area lies in eight states and union territory of Delhi. The percentage of catchment area in each state is (Rao, 1975):

1. Uttar Pradesh - 34.2%
2. Himachal Pradesh - 0.5
3. Punjab and Haryana - 4.0
4. Rajasthan - 13.0
5. Madhya Pradesh - 23.1
6. Bihar - 16.7
7. West Bengal - 8.3
8. Union territory of Delhi 0.2

Geology and Geography of the Basin:

Geology: A brief geology of the Ganga River Basin is given here. The percentages of various rocks present in the basin are listed in the table 3.1. The general geology is shown in Fig. 3.2.

The geology of the area under present study can be devided into extra peninsular and peninsular geology for convenience. They are being separated by Indo-gangetic planes. In the extrapeninsula the Archaean granite and gneisses are present in small patches in the Gangotri region. The Palaeozoic rocks in this region is represented by Haimanta System and Garbyang Series consisting of slates, quartzites, shales, micacious quartzites, some dolomite, phyllite, fine grained calcarious sandstone and some argillaceous dolomites. In the Mesozoic the dominant rocks are limestone, shale, shaly limestone and sandy limestone. The Tertiaries are represented by Siwaliks System consisting mainly of sandstones, grit, conglomerate, clays and silts. Some of the latest deposits are made up of flood deposits.

The alluvium constitute about 57% of the total basin (in India). Most important among those are a part of Indo-gangetic alluvium which separates the Himalayan mountains in the north from hills and plateaus

Table 3.1: Distribution of rock types in Ganga River Basin in Percent

	Deccan and Rajmahal Traps	Granites, Gneisses and Charnockites	Archaean granites and gneisses	Cambrian and upper pre-Cambrian Haimanta, Vindhyan and Kurnool	Others Oh	Alluvium
Yamuna	19	6.5	10.5	15.7	0.6	47
Ramganga					13	87
Gomti						100
Son		13.5		72.5		14
Gandak						100 (in India)
Ghaghara						100 (in India)
Over all	10	11	5	16	1.75	57

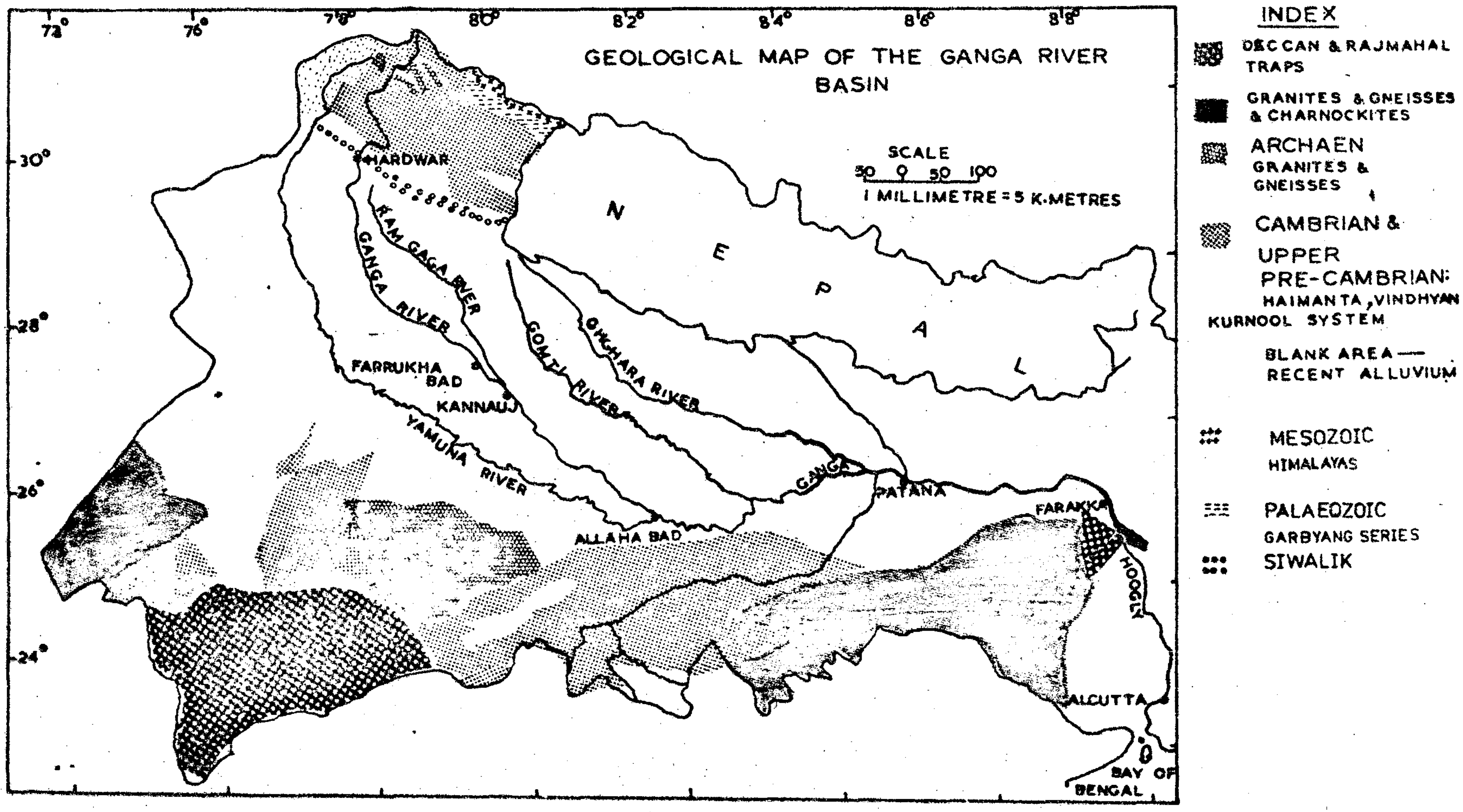

Fig. 3.2: Geological map of the Ganga River Basin.

in the south. They are upto 1000 meter thick and composed of gravels, sand and clays. The older alluvium called Bhangar is rather dark coloured and generally rich in concretions and nodules of impure calcium carbonates known as Kankar. The newer alluvium is light coloured and poor in calcarious matters. It contains lenticular beds of sand, gravels and peats (Krishnan, 1968).

The Archaean granites and gneisses in the peninsular region is represented by Bundelkhand granites and gneisses in area under study. The rocks are composed of quartz, pink orthoclase, perthite, plagioclase some biotite and hornblende. Granite gneisses and charnockites are present in south eastern part with some Khondalite association. The charnockite also forms hybrid gneisses with Khondalites and some other ancient gneisses.

The upper part of pre-Cambrian and Cambrian in the area is represented by Vindhyan and Kurnool system. The dominant rock types are sandstones of different varieties, limestones and shale.

In parts of the Son River Basin, Gondwana rocks are encountered which are represented by different cycles of sandstone shale and coal seams.

Vast basaltic flows are seen in the south-western part of the basin called Deccan Traps. They are mostly fissure eruption of basaltic composition forming plateaue basalt. At the border of Bihar and Bengal, the Rajmahal Traps which resembles very much to Deccan Traps in composition are exposed. They vary from dolerite to basaltic depending on their texture. Thus, the basin has got a very varied geology representing rocks from pre-Cambrian to latest flood deposits.

Geography: The Ganga River Basin covers a wide variety of land-forms from featureless plains in the central east-west belt to hanging valleys and glaciers in the north and plateaues and hills of south. The elevation of the basin ranges from 7010 meters for Gangotri Glacier to barely few meters for Calcutta.

The basin has annual monsoon rainfall averaging from 1500 to 2120 mm near delta, 1000 mm in the middle part and 750 mm towards western end (UN, 1966). The climate of the upper Ganga Plain is subhumid and perhumid in lower Ganga Plains. The middle Ganga Plains has humid climate between relatively drier upper Ganga and perhumid lower Ganga Plain. The climate in the Himalayan region is also humid.

CHAPTER IV

METHODOLOGY

Sampling Procedure :

The Ganga water samples were collected during monsoon of 1981 (July-August). For each sample, two litres of water was collected from the surface of water in polythene bottles. pH was measured by pH paper in the field and sample sealed with wax were sent to laboratory where they were kept in cold room (temp. 3°C) to avoid organic decay, chemical interaction, etc.

The samples were collected from both the banks and two samples were collected from each sampling point. The sampling stations are shown in the Fig. 3.1. The Ganga was sampled at various points keeping into the mind that samples should be collected before and after mixing of each tributary. Simultaneously the tributary samples were also collected to get the idea of geochemistry of various sub-basins and their impact on the main river. The processes operating in various sub-basins reflect the geochemistry of whole basin with their integrated effect.

Sampling of Suspended Matter :

Each bottle containing one litre of water was emptied with its sediment content in different beakers. The beakers were kept undisturbed to allow the sediment to settle down. After a week, the water from each beaker was filtered through a dried and preweighed Maxflow membrane filter (pore size 0.45 microns) to catch the finer sediments still unsettled. The vacuum pump was used to create the suction. The sediments left in the beakers were dried on waterbath and were taken out and weighed after drying. The weight of the sediment on the filter paper was added to the weight of the sediment obtained from the beakers. This total sediment weight gives the amount of total suspended matter.

Half of each suspended sediment sample was treated with hydrogen peroxide (H_2O_2) and washed with distilled water to remove organic matters. Slides were prepared for X-ray mineralogical study from organic free sediments. The rest of the samples were packed in polythene bags. The filtrates were stored in polythene bottle for water analysis.

Water Analysis :

The pH and conductivity of every sample was measured as soon as they were brought in the laboratory. The filtered water samples from all the stations were analysed for various species present in the system. Standard methods were applied to estimate various species by titration, spectrophotometry, etc. accordingly suitable.

Chloride and bicarbonate were estimated by titration. Silica, sulphate and phosphate were determined by spectrophotometer while sodium, potassium, magnesium and calcium were analysed by atomic absorption spectrophotometer. Fluoride was measured by ion meter using selective ion electrode.

pH :

The pH of water sample was measured by Elico pH meter. The instrument was set for pH 7 buffer at temperature 23°C.

Conductivity :

Specific conductivity was measured in µ MHO/cm using Systronic direct reading conductivity meter-303. The instrument was chliberated and set for 0.1 KCl standard. The measurement was made at 23°C.

Chloride :

Chloride was estimated by titrating standard chloride solution of various concentrations against silver-nitrate ($AgNO_3$). Potassium chromate (K_2CrO_4) was used to indicate the end point. The volume of silvernitrate solution consumed to reach the end point was recorded from the burette. A standard graph was plotted against the concentration of standard chloride and the volume of silver nitrate solution consumed. The chloride in the various samples were determined by comparing their consumption of silvernitrate with the standard graph.

Bicarbonate :

The estimation of bicarbonate was done in the field by titrating the standard bicarbonate solutions against 0.006 N hydrochloric acid using methyl orange as an indicator. A standard graph was plotted for the volume of HCl consumed against various standard strengths of bicarbonate solutions. The amount of bicarbonate present in the various samples are measured after comparing their readings with the standard graph.

Bicarbonate was again estimated in the laboratory just after the samples were reached. In this method no indicator was used instead, pH meter electrode was dipped into the solution and HCl was added to it through a burette. The volume of 0.006 N HCl to bring the pH of solution at 4.5 was noted and a graph was plotted as above to calculatedthe values for bicarbonate in the samples. The average value of the two methods is taken for the various calculations in the text.

Fluoride :

For the estimation of fluoride, cornning pH/Ion Meter-135 was used. First the instrument was caliberated for the standard fluoride. Hundred ml of each water sample was pipetted out and 100 ml of TISAB (425 g/l sod.chloride, 58.5 g/l acetic acid glacial, 66 g/l sod.acetate and 1 g/l CDTA-1,2 cyclohexylene diamene tetra acetic acid) was added and mixed thoroughly to suppress the interference of the other ions.

Silica:

Standard solution of 0.5, 1, 2, 5 and 10 ppm SiO_2 was prepared by dissolving Na_2SiFe and diluting the solution in various proportions. 25 ml of each standard and water samples was taken out.

In this 10 ml ammonium molybdate solution (the solution is prepared by dissolving 2 grams of ammonium molybdate in 10 ml of distilled water and adding 6 c.c. of conc. HCl. This solution is then diluted to make the total volume 100 c.c. by adding distilled water) and 15 ml of reducing reagent was added (prepapred by mixing 100 ml metal sulphite solution, 60 ml of 10 per cent oxalic acid and 120 c.c. of 25% sulphuric acid and diluted by distilled water to make up the volume to 300 ml. Metol sulphite solution is prepared by dissolving 5 g of metol in 210 ml of distilled water. Again 3 grams of sodium sulphite is added and dissolved and distilled water is added to make up the volume upto 250 c.c.). The samples were stirred properly and kept for 3 hours to let the reaction be completed. The optical density was measured for standard and river water samples at 812 mμ using Beckman model 34 Spectrophotometer. A standard graph was plotted for standard silica concentration versus optical density (absorption). The silica in the water samples were estimated by comparing their optical density, values with the standard graph.

Sulphate :

Sulphate standards were prepared for 2, 5, 10, 20, 25 and 50 ppm concentrations. Twenty ml of each water sample and standard solutions were taken out in beakers. In this was added NaCl-HCl solution and glycerol-alcohol solution, ten ml each (NaCl-HCl solution is made by dissolving 240 g of NaCl in about 900 ml of distilled water. In this 20 ml of conc. HCl is added and total volume is made upto one litre by adding distilled water. Glycerol-alcohol solution is the mixture of one glycerol and two part ethyl alcohol). Barium chloride solid 0.15 g was added and the mixture was placed on magnetic stirrer for few minutes. The extinction was measured after 30 minutes, 820 mμ by B$\overset{u}{a}$sch and Lomb Spectronic-20.

Phosphate :

Phosphate standard solution of different concentration ranging from 0.01 ppm to 5 ppm were prepared by from Potassium dihydrogen phosphate (KH_2PO_4). Four ml from each standard and water sample were pipitte out into a 100 ml volumetric flask and 5 ml of molybdate solution and 2 ml of ascorbic acid solution was added and mixed well. The mixture was diluted to 100 ml and extinction was measured at 882 mμ after ten minutes. Molybdate solution is prepared by dissolving 4.8 g of ammo.molybdate $(NH_4)_6.Mo_7O_{24}.4H_2O)$ and 0.1 g of sodium antimonytartrate $(NaSbOCuH_4O_6)$ in 400 ml of $4N-H_2SO_4$ and making the total volume upto 500 ml with the same sulphuric acid. Ascorbic acid (about 0.1 M) is prepared by dissolving 2.0 g of ascorbic acid in 100 ml water. This solution is usable for one week if kept in refrigerator.

Sodium and Potassium :

Sodium and potassium were analysed by Carl Zeiss AAS-I spectrophotometer in emission mode. The standard graph was made for estimation of sodium and potassium.

Calcium and Magnesium :

Calcium and magnesium were analysed in absorption mode by Carl Zeiss AAS-I spectrophotometer. Various standards of calcium and magnesium were run and values were plotted in standard graph. The values of the water samples were compared with standard graph to get the concentration of magnesium.

Mineralogy :

The X-ray slides were prepared from the suspended sediments by 'drop on slide' technique (Gibbs 1967). The X-ray diffractograph were taken by Philips X-ray Diffractometer using CuKα radiation and Ni filter. The chart drive was 1 cm/min and intensity 2 x 10^2. The mineral identification and abundance were done by following the methods of Biscaye (1965) and Carrol (1970).

CHAPTER V

RESULTS AND DISCUSSIONS
WATER CHEMISTRY

The chemical composition of the samples collected during monsoon for the Ganga and its tributaries are listed in tables 5.1 and 5.2 respectively.

pH

The pH of the Ganga ranges from 7.7 to 8.0. It is almost the same as reported by Handa (1972), Raymahashaya (1970), Subramanian and Dalavi (1978). The pH values for Mekong reported by Corbonnel and Meybeck (1975) is also nearly the same as that of the Ganga. Thus, the river water is slightly alkaline as most of the rivers of the world. Garrels and Mackenzie (1971) pointed out that the chemically active rivers should be alkaline and the results show that all the samples analysed are alkaline.

The river is less alkaline in the upstream region as compared to the downstream, because of the addition of more alkaline water from the tributaries like the Ghaghara, Son and Gandak. The alkalinity may also be controlled by the precipitation.

Table 5.1: Chemical composition of the Ganga River (Monsoon 1981).

Sample Location	pH	Conductivity μMHO/cm	HCO_3^-	Cl^-	F^-	SO_4^{--}	PO_4^{---}	SiO_2	Ca^{++}	Mg^{++}	Na^+	K^+	TDS	TSM
Rishikesh	7.9	175	61.25	3	0.1	19.5	0.07	4.0	17.5	5.0	3.0	3.5	117	-
Hardwar	7.7	155	52.0	2	0.1	8.5	0.06	3.0	27.5	6.3	2.5	3.0	105	608
Kannauj	7.7	245	97.0	4	0.2	7.0	0.25	1.5	38.0	6.0	5.5	5.5	165	387
Farrukhabad	7.8	220	86.5	2	0.2	13.5	0.01	3.3	45.0	5.0	4.5	5.0	165	110
Allahabad														
Before mixing	7.8	225	95.0	3.5	0.2	11.0	0.02	2.3	46.0	6.0	5.5	4.5	174	965
Confluence	7.9	250	96.0	7	0.2	7.5	0.03	3.3	15.0	6.0	12.5	2.2	150	1844
After mixing	8.0	222	109.0	3.5	0.2	10.0	-	3.2	45.0	5.0	5.5	4.5	186	1506
Varanasi	7.8	250	95.0	7	0.2	7.5	0.35	3.7	40.0	6.3	10.5	4.0	175	1732
Ghazipur	8.0	250	206.0	6	0.2	7.5	0.04	3.0	43.0	5.3	15.0	4.0	290	1231
Sonpur	8.2	255	100.0	8	0.2	6.0	-	2.0	40.0	6.0	13.5	4.0	180	3317
Patna	7.8	295	116.0	10	0.2	12.0	0.09	3.5	50.0	7.0	13.5	4.0	216	1518
Farrakka a-	7.9	200	82.5	7	0.1	2.5	0.04	3.1	45.0	5.0	4.5	3.0	153	3093
b-	8.0	205	86.0	4.5	0.1	7.0	-	3.1	45.0	5.0	5.0	3.5	159	3226
Calcutta a-	7.8	235	104.0	7	0.2	5.0	0.05	3.0	36.5	5.0	8.5	3.5	173	875
b-	7.7	212	90.0	12	0.2	7.0	0.02	3.5	38.0	6.0	9.5	4.0	170	521
c-	7.7	215	81.0	8	0.2	7.0	0.04	3.5	36.5	5.0	9.0	4.0	154	601

Table 5.2: Chemical composition of the tributary of the Ganga River (Monsoon, 1981)

Name ofthe Tributaries	pH	Conductivity uMHO/cm	ppm											
			HCO_3^-	Cl^-	F^-	SO_4^{--}	PO_4^{---}	SiO_2	Ca^{++}	Mg^{++}	Na^+	K^+	TDS	TSM
Ramganga	7.6	260	107	3	0.2	11.0	0.11	3.4	42.5	8.0	7.0	4.0	186	718
Yamuna	7.8	287	111	10	0.2	9.0	0.34	3.2	37.0	6.0	12.5	4.0	193	1349
Gomti	7.6	235	96	4.5	0.2	7.0	0.08	2.5	3.3	6.0	15.0	4.5	169	925
Ghaghra	8.0	222	100	3	0.1	8.5	0.01	2.5	50.0	6.0	3.0	3.0	176	1326
Son	7.8	285	111	9	0.2	11.0	0.36	4.3	53.0	6.5	15.0	4.0	214	1589
Gandak	7.9	230	97	2	0.1	14.5	-	3.0	43.0	6.0	3.0	4.0	173	472

It has been reported by Subramanian and Saxena (1980) that bicarbonate concentration in the rain water increases with increase in rain fall, hence an increase in alkalinity in downstream region is expected because of more rain fall in that region.

Conductivity:

The specific conductivityof the Ganga River water rages from 155 µMHO/cm to 295 µMHO/cm. There is a general increase in the conductivity downstream, because of the addition of high conductive waters from tributaries. The high conductivity in the downstream may also be because of the addition of rain water having higher Na^+ and Cl^- ions coming from the recycling of sea water. The higher concentration of Na^+ and Cl^- in rain water of the regions closer to the sea has been reported by Garrels and Mackenzie,(1971).

The bicarbonate and calcium are the two major constituents of the river water. The bicarbonate constitutes about 51% and calcium about 23% of the total dissolved solids. At present, I am unable to explain the abnormally high concentration of bicarbonate at Ghazipur satisfactorily, but the experimental and instrumental errors can not be ruled out.

It is interesting to note the variation of Na^+/K^+ ratio. In the upstream area (Rishikesh and Hardwar) the value is 0.86 and 0.83 respectively and increases to 1 at Kannauj and continuously increases upto Patna (3.38). It goes down at Farakka but increases again at Calcutta. The observation clearly indicates that the sodium is not only coming from the weathering of the rocks but also from the other sources and most probably from the cycling of the sea water through precipitation while potassium is coming mainly from the weathering and hence remains almost constant throughout the course of the river.

The Ca^+/Mg^+ ratio varies from 3.5 in the source area to 7.4 in the down stream at Calcutta, showing a relative increase of calcium down stream. The high calcium may be because of the addition of Calcium from the Kankar carbonate rich alluvial terrain mentioned by Subramanian (1979).

The quartz and amorphous silica can be dissolved upto 13 and 130 ppm respectively in the river waters in form of $H_4SiO_4^*$. All the samples analysed show under-saturation of silica with respect to quartz and amorphous silica. Subramanian and Dalavi (1978) have reported higher values of silica concentration (8-14 ppm) for the

Ganga River based on dry and wet season sampling, even then the analysis revealed undersaturation of silica. Handa (1972) has also reported higher concentration of silica for the Ganga River.

Total Dissolved Salts (TDS):

Downstream variation: Downstream variation in TDS is shown in fig. 5.1. There is a general increase in the dissolved salts downstream. This has been observed by various workers (Gibbs, 1967; Carbonnel and Meybeck, 1975; Bikshamaiah and Subramanian, 1980, etc.). There is very high value at Ghazipur because of abnormally high value of HCO_3^-. At Patna, the concentration increases not because of addition of more concentrated water from tributaries but probably because of the human interference. The dissolved solids concentration at Calcutta increases as compared to Farakka, but no high concentration for sodium or chloride ions is observed indicating unmixing with the sea water upto that place. Because of the high discharge during monsoon the mouth of estuary remains far off in the sea and hence the mixing of sea water is restricted only in that region But in the low discharge period, because of the influx of tidal water, the river water chemistry may be affected even upto Calcutta (Handa, 1972).

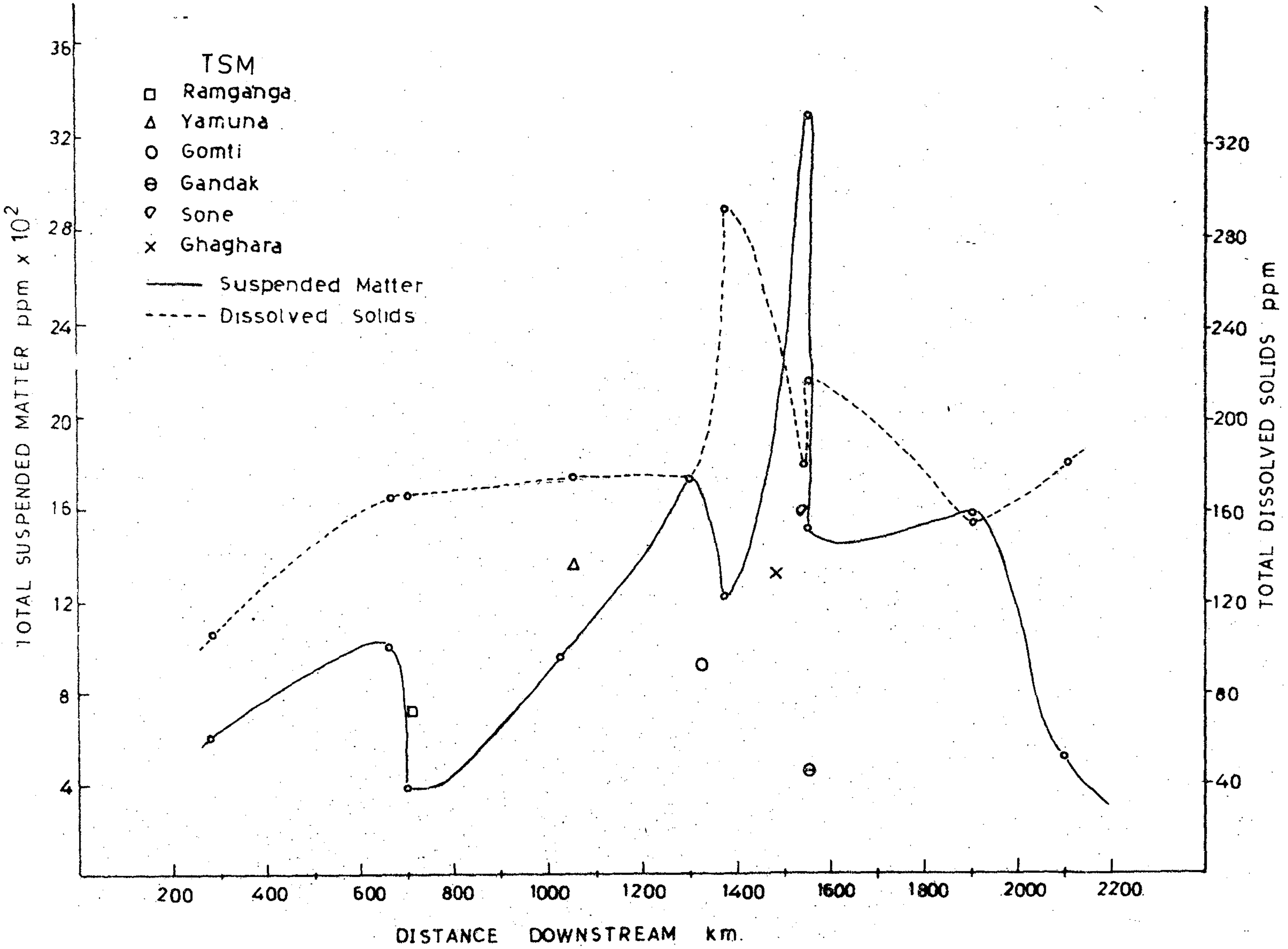

Fig. 5.1: Downstream variation in TDS and TSM

The control of elevation on TDS as mentioned by Gibbs (1967) for the Amazon is not observed in the Ganga River Basin. The values of dissolved solids concentrations are uncorrelated with elevation. Son, with an elevation of 325 meters has got highest TDS (214 ppm). The Gandak and Ghaghra having very high elevation as compared to the Son have much lower dissolved solid concentrations (172 and 176 ppm respectively). The Yamuna is having high dissolved solids with high elevation. The Son gets high dissolved solids from the sedimentary rocks of Vindhyans comprised of shale, limestone and sandstones. Same is the case of the Yamuna, which receives the Betwa, Chambal, etc. draining the basic igneous rocks, highly susceptible to chemical weathering giving high dissolved load. This has been observed for a large number of African rivers (Grove, 1972). These rocks having vesicles and cavities provide enough time for water to react and add dissolved salts to the solution. The dominance of rock-type in controlling dissolved solids has also been reported by Bikshamaiah (1979) for the Godavari and Carbonnel and Meybeck (1975) for the Mekong River.

In fig. 5.2, the dissolved solid concentrations are plotted against the suspended solids concentrations. The plots fall in a zone shown by broken lines. In general there is an increase in dissolved solid concentration with increase in suspended solid concentration.

Total Suspended Matter:(TSM):

TSM is one of the important parameters of the river basin studies. It has been taken as the index of physical weathering in the catchment area, hence is used to calculate the sediment load of the river. Downstream variations in the TSM have been studied by various workers like Gibbs (1967), Bikshmaiah and Subramanian (1980), Carbonnel and Meybeck (1976), Subramanian (1979) etc. There is a general decrease in TSM downstream mainly because of the alluvial sedimentation and also because of concentration of artificial barrage etc.

Downstream variation: Downstream TSM variation is shown in figure 5.1. It is generally increasing downstream upto Patna and then gradually decreases. The decrease in TSM between Farrukhabad and Kannauj is perhaps due to sampling problems and not because of the dilution by the Ramganga River. The river at this

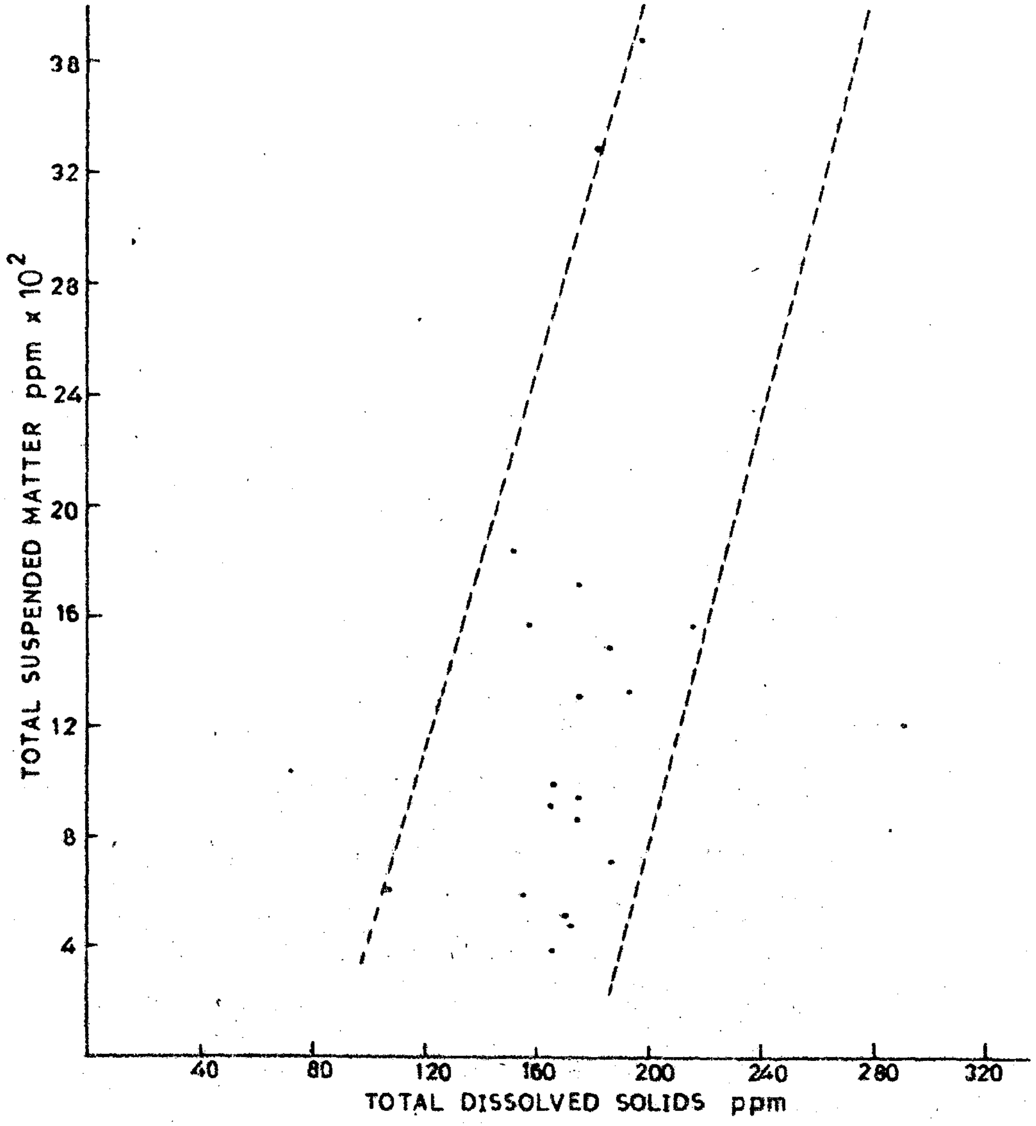

Fig. 5.2: Showing a General Increase in TSM with TDS.

place is braided and the sample was collected only from one of the branches. So there are every possibility of getting low TSM. There is an increase in suspended matter from Kannauj to Varanasi. The River Yamuna with higher TSM than the Ganga joins at Allahabad. Between Varanasi and Ghazipur, the TSM decreases apparently because of the dilution by the Gomti River. At Sonpur, (after mixing with the Ghaghara) the river has got abnormally high TSM value (3316 ppm) which decreases at Patna. After a slight increase at Farakka, finally TSM decreases at Calcutta. Very high value of TSM at Sonpur (near Patna) is mainly due to human activities. The TSM value at Calcutta may be controlled with the artificial Farakka Barrage which regulates the flow in the Hoogly and Padma. The alluvial sedimentation between Farakka and Calcutta, may be other important reason for the decrease in TSM at Calcutta. After Farakka the river takes a bend and almost becomes north-south. This will certainly reduce the velocity of the stream water and a considerable amount of alluvial sedimentation may take place, hence TSM is decreased downstream at Calcutta.

In the Ganga River Basin, the TSM does not seem to be correlated with elevation as it has been pointed out by Gibbs (1967) for the Amazon River. Here, the high TSM is for the river draining areas of mid-altitude with sedimentary and metaigneous rocks. This type of observation is also reported by Bikshamaiah (1979) for the Godavari River. For example, the Son with lowest average elevation and low discharge (31800 million cubic meters/year) as compared to the Gandak (52200 million cubic meter/year) has got maximum TSM (1589 ppm). The Son has about 80% of its drainage area in the Vindhyan rocks comprising of shale, sandstone and limestone. The Yamuna which receives tributaries draining Vindhyans, Deccan Traps and some granitic rocks has got high TSM.

This shows that rock type and percentage of the rocks covering the basin area are important factors to control TSM concentration. The control of rock type has been reported by various authors - Subramanian and Dalavi,(1978), Emery and Milliman (1978), Bikshamaiah (1979), etc.

From the preceding discussions, it is clear that the rock type is the main control over the TDS and TSM concentration in the Ganga River Basin. The elevation, which is the most important factor in controlling TDS and TSM for the Amazon is not important for the Ganga, because of its different varied geological and geographical set up.

The control of water chemistry on the concentration of suspended matter in the Ganga River has been attempted in the following paragraphs. The control of water chemistry on the suspended solids concentration has been discussed by Imeson and Verstraten (1981) for rivers like the Pipe Clay Creek, New South Wales; Qued Kala Iris, Morocco; Moreau River, Bixbay, S. Dakota; Catchwater Drains, Yorkshire, England.

The nautral waters having low or intermediate level of electrolyte-concentration with high sodium concentration, may bring about the dispersion of clay. The water carrying clay dispersion in suspension may flocculate if the chemical environment changes. Dispersion is likely to occur if soils in the drainage basin have high percentages of exchangeable sodium (ESP). The chemical balance between dispersion and flocculation in stream water, is determined amongst other things, by the thickness of the diffuse double layer around the particles, which reflects both the chemical composition of this layer and the stream water chemistry, i.e., its electrolyte content. At high electrolyte concentrations, particle agglomeration generally occurs at maximum rate, being determined almost solely by diffusion (rapid coagulation). At intermediate electrolyte concentrations, the coagulationproces is retarded by the long-range repulsion and slow coagulation takes places. At low electrolyte concentration, the coagulation process is retarded to such an extent by the appreciable high range repulsion that for all practical purposes, the suspension is stable under these conditions (Van Olephen, 1977).

The cationic composition within the diffuse double layer and its thickness can be established if it is assumed that the accumulation of cations is governed by electrostatic attraction. The ratio of adsorbed cations is then a function of the so-called 'reduced concentration ratio' of the cations in the stream waters, if the ionic strength is not too high. This reduced ratio, for a simple mono-divalent system like Na-Ca water, is defined as

$$Co(Na)/\sqrt{(Co(Ca))}.$$

in which Co is molarity of the ions in the aqueous solutions (Imson and Verstraten, 1981).

For most natural water system, the reduced concentration ratio is equivalent to the sodium absorption ratio (SAR),

$$SAR = \frac{Co\ (Na)}{\sqrt{\left(\left\{ Co(Ca) + Co(Mg)\right\}/2\right)}} \left(m\ moles/l^{1/2}\right)$$

in which concentrations are expressed in meq/l.

In fig. 5.3, the electrolyte concentration (≤ cat) is plotted against the SAR values of the water sample. The SAR value increases with the electrolyte concentration. The increase is not in equal proportion. There is more increase in the concentration of sodium with little increase in electrolyte concentration (≤ cat).

This is evident from the Fig. 5.4, that no individual ion is directly controlling the suspended solid concentration, since no definite pattern is observed between suspended solids concentration and Na, Ca + Mg, and ≤ cations.

In Fig. 5.5, the percentage of Na in total cation and SAR value are plotted against the TSM. The high values of TSM is generally correlated with the high percentage of sodium and higher value of SAR. This shows

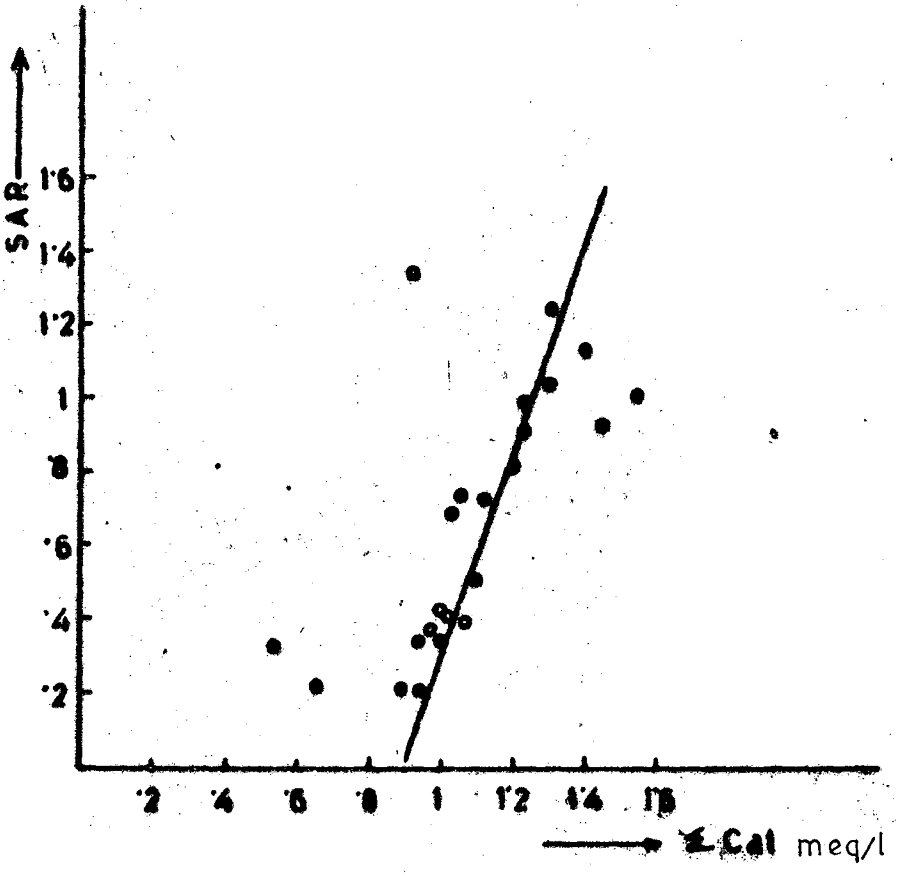

Fig. 5.3: Showing increase in SAR with Σ cat.

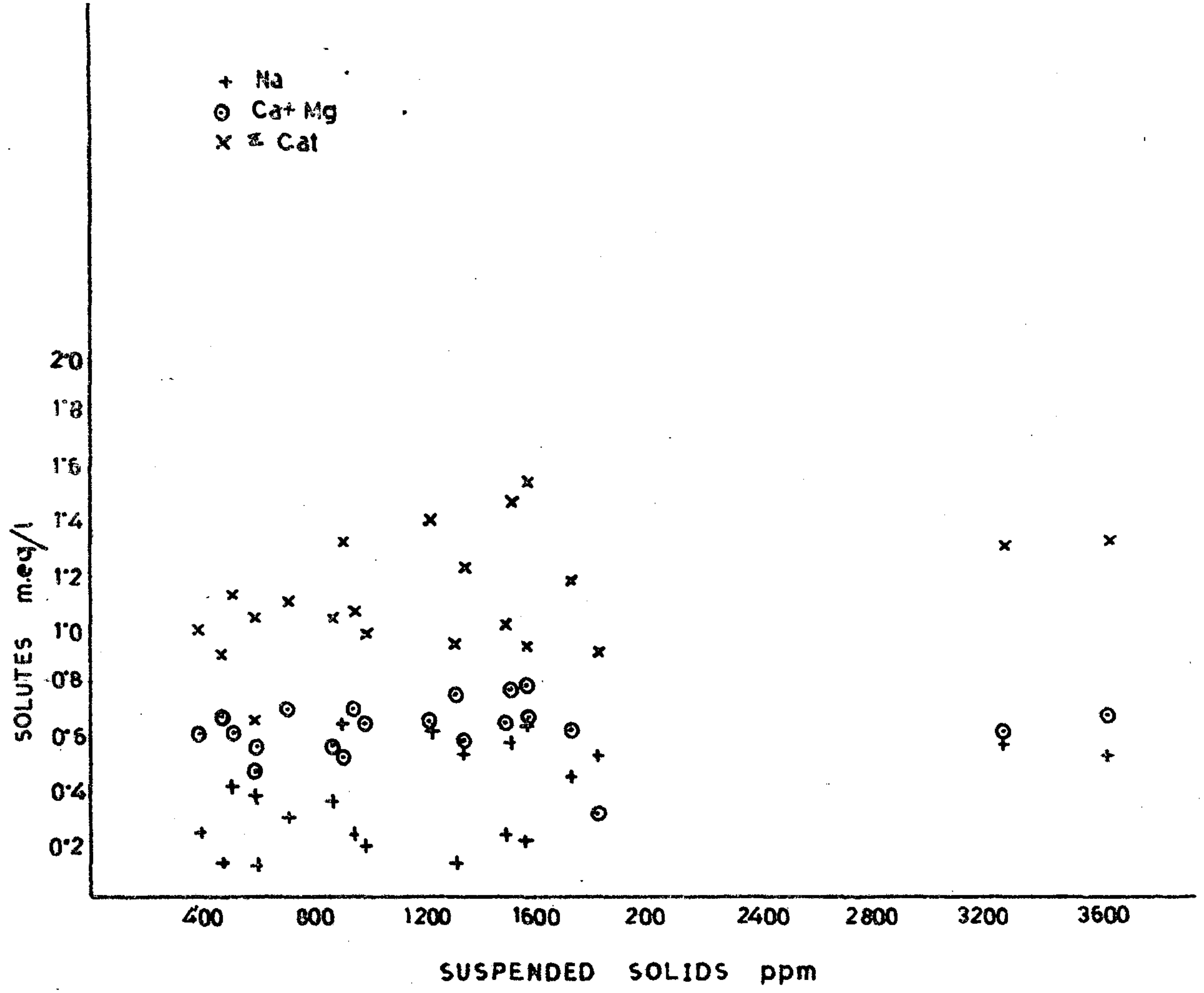

Fig. 5.4: Showing suspended solid concentration independent of a particular cation concentration.

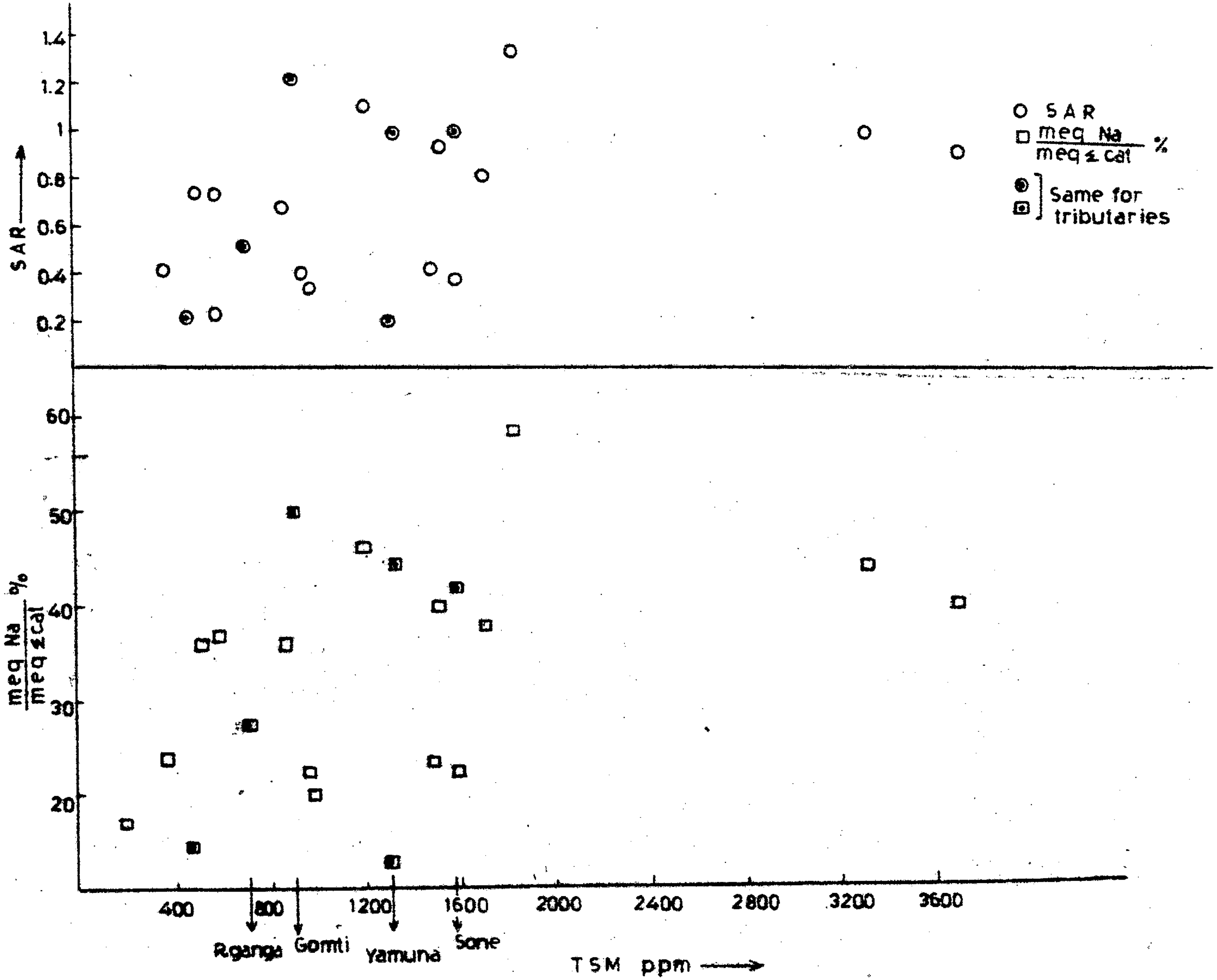

Table 5.5: Showing increase in suspended matter concentration with SAR and sodium percentage.

a control of exchangeable sodium on the suspended solids in river water. At high percentage of sodium and low electrolyte conbentration the clay particles are dispersed into the water, hence increase the TSM.

Thus, the concentration of suspended solids in the Ganga River Basin, is not only controlled by physical parameters only but also partly by the chemistry of river water.

Mineralogy of The Suspended Sediments:

In this section, an attempt is made to theoretically predict the possible minerals in equilibrium with the river water. To conform these predictions, and to get a quantitative result, the suspended sediments mineralogy was studied by taking their X-ray diffractographs.

Mineral equilibria in the $CaO-MgO-CO_2-H_2O$, system: In orthogonal stability diagram (fig. 5.6) the logarithm of the observed (PCO_2) and $\left[\frac{Ca^{+2}}{Mg^{+2}}\right]$ were plotted as variables. It is found that all the points are clustered in dolomite field. It is also observed by Subramanian (1979). In most natural water, the dolomite does not precipitate, except in some hot springs, salt-lakes and in muds of salt lagoons undergoing strong solar evaporation. It is believed that the dolomites are

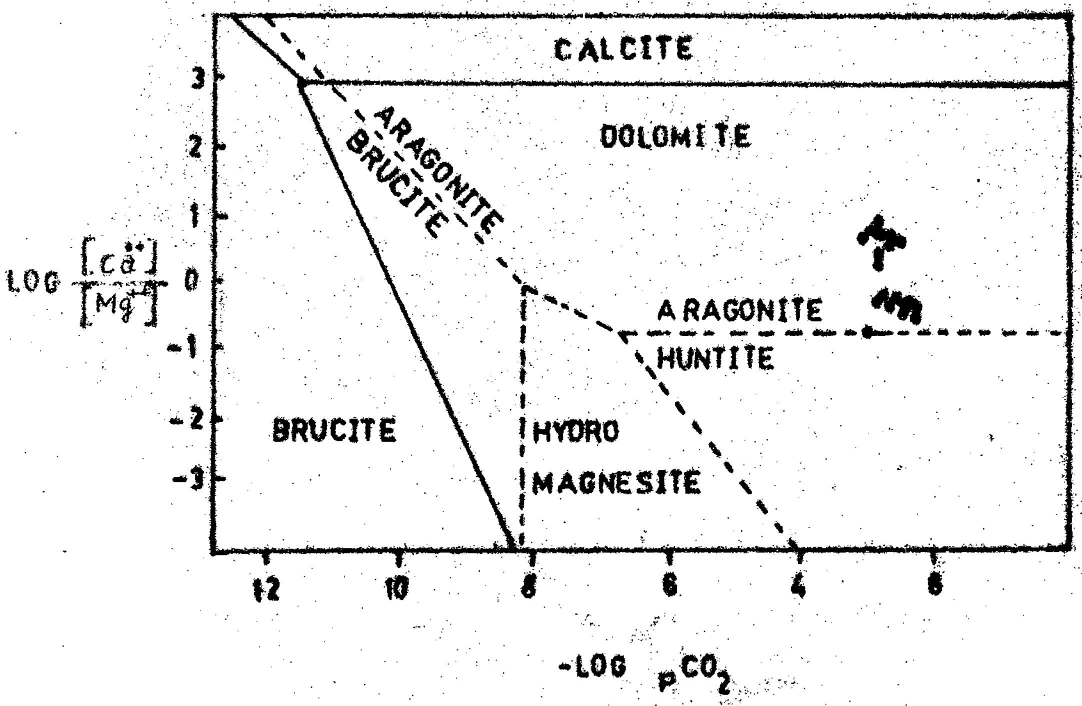

Fig. 5.6 CaO – MgO – H_2O-CO_2 System

Showing dolomite in equilibrium with river water.

formed by conversion of calcium carbonate after deposition. But the X-ray diffraction studies of the suspended sediments show that the dolomite is present in small amount in almost all samples. These dolomites may not be a primary precipitate but the clastic dolomite present in fine clays and silt suspension.

Mineral Stability in silicate system

Na_2O-K_2O-CaO-MgO-Al_2O_3-SiO_2-H_2O: System: To predict the possible silicate minerals in equilibrium with the river water, activity-activity diagram is made for Na-silicate, K-silicate, etc. In the diagram, the log. of activity of respective cation/activity of hydrogen ion are plotted against the negative log of activity of silica.

The plots are shown in Fig. 5.7 A,B,C,D.

It is clear from the Fig. 5.7 A, D and C that kaolinite is the possible clay mineral. In no case, gibbsite seems to be in equilibrium with the water. This observation conforms the general observation that kaolinite is the most common clay mineral produced by by the weathering of silicates. Since gibbsite requires a continuous flushing out of the silica by rain water, its probability is very much reduced in a basin like that of Ganga River.

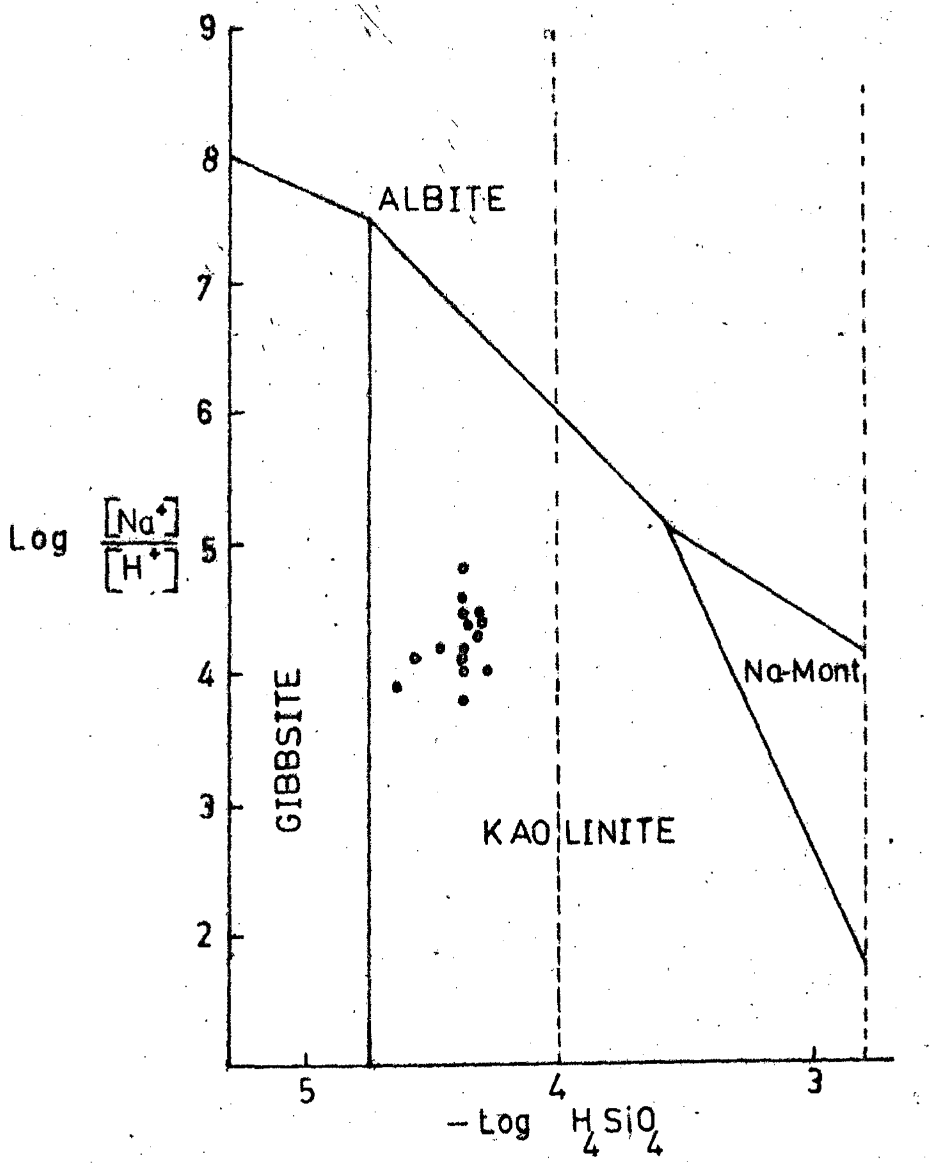

Fig. $Na_2O - Al_2O_3 - SiO_2 - H_2O$-System

5.7A: Showing kaolinite as possible clay mineral in equilibrium with river water.

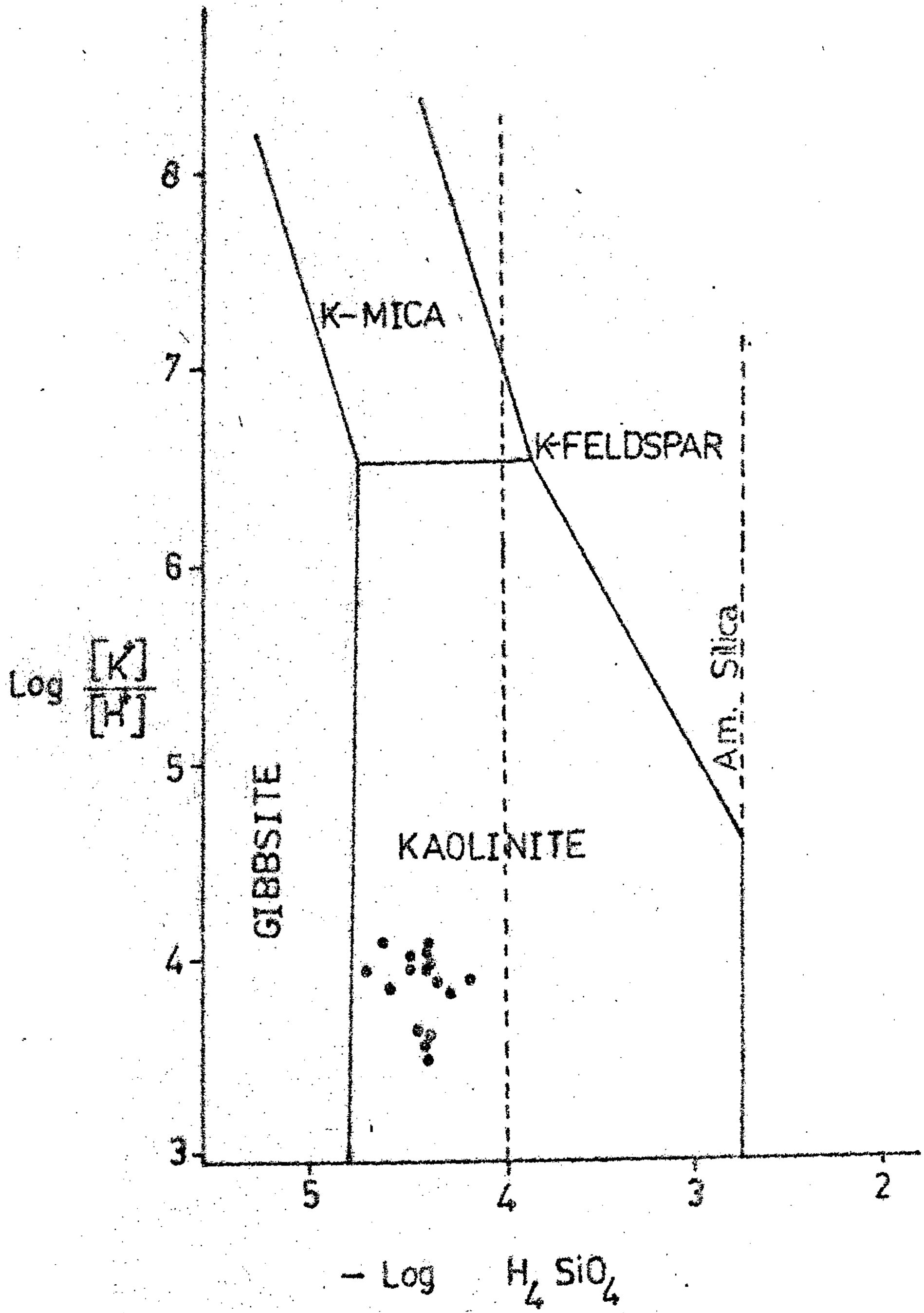

Fig. 5.7B $K_2O-Al_2O_3-SiO_2-H_2O$ System

Showing kaolinite as possible clay mineral in equilibrium with river water.

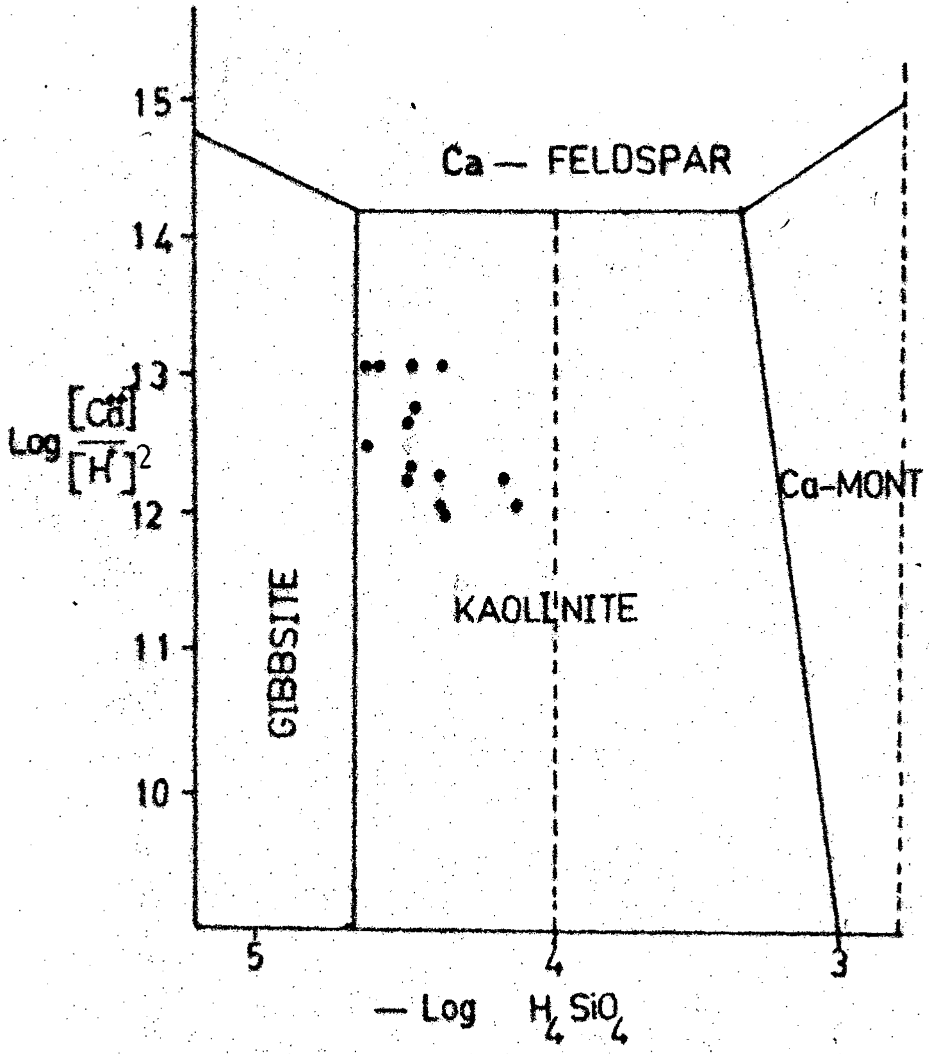

Fig. $CaO-Al_2O_3-SiO_2-H_2O$ System

5.7C : Showing Kaolinite as possible clay mineral in equilibrium with river water.

Fig. 5.7 D shows the possibility of chlorite in Mg-silicate system. This observation is also made by Subramanian and Dalavi (1978)

The abundance of the various minerals present in suspended sediment is listed in Table 5.3. These results are at best semiquantitative. The relative abundance of the minerals is calculated by the relative area occupied by the characteristic peak at particular d-spacing. In Fig. 5.8, some of the diffractographs are given and the position of the characteristic peaks are marked.

Quartz and felspar: Quartz and felspar both are resistant to physical weathering but felspar is quite susceptible to chemical weathering and gives rise to clay minerals when it weathers out. Gibbs (1967) reported for the Amazon that quartz is less abundant in mountaneous environment. The high percentage of quartz at Hardwar (mountaneous environment) may be because of breaking down of quartz by some physical processes which are not operative in Amazon River Basin. The high relative percentage of quartz may be because of relative absence or deficiency of other minerals like clays.

The mineralogy of Yamuna river is interesting. It drains through the area similar to the Ganga in upper

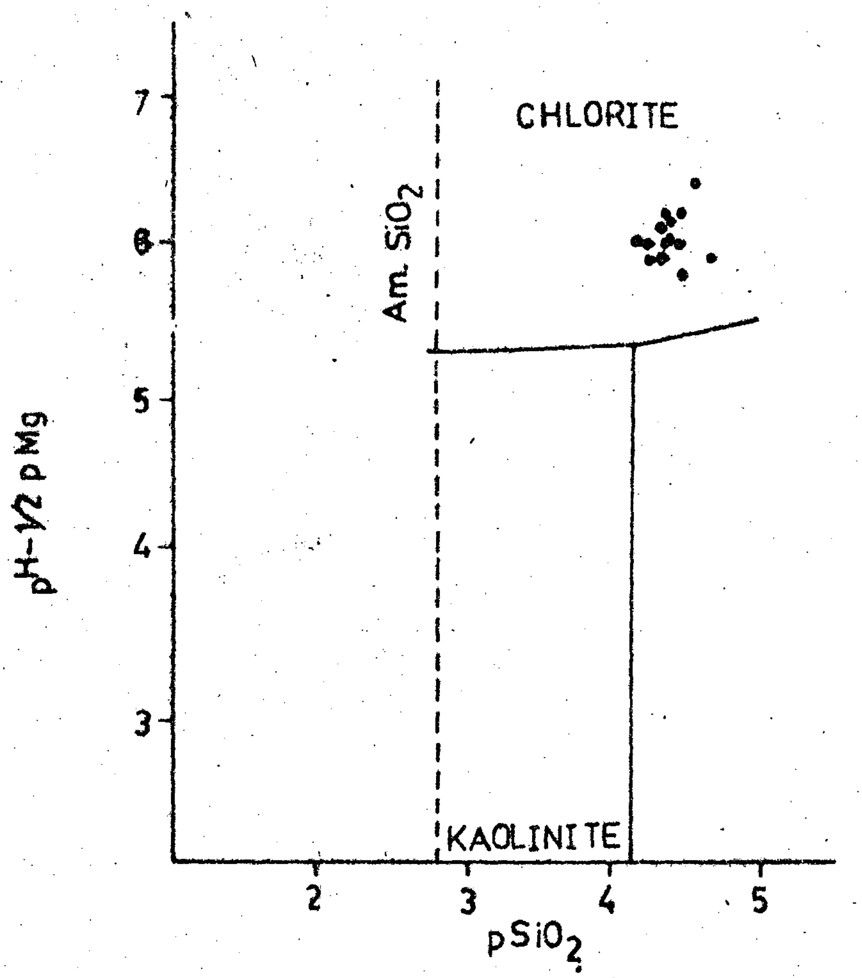

Fig. $MgO-Al_2O_3-SiO_2-H_2O$-System

5.7D : **Showing the possibility of chlorite in equilibrium with river water.**

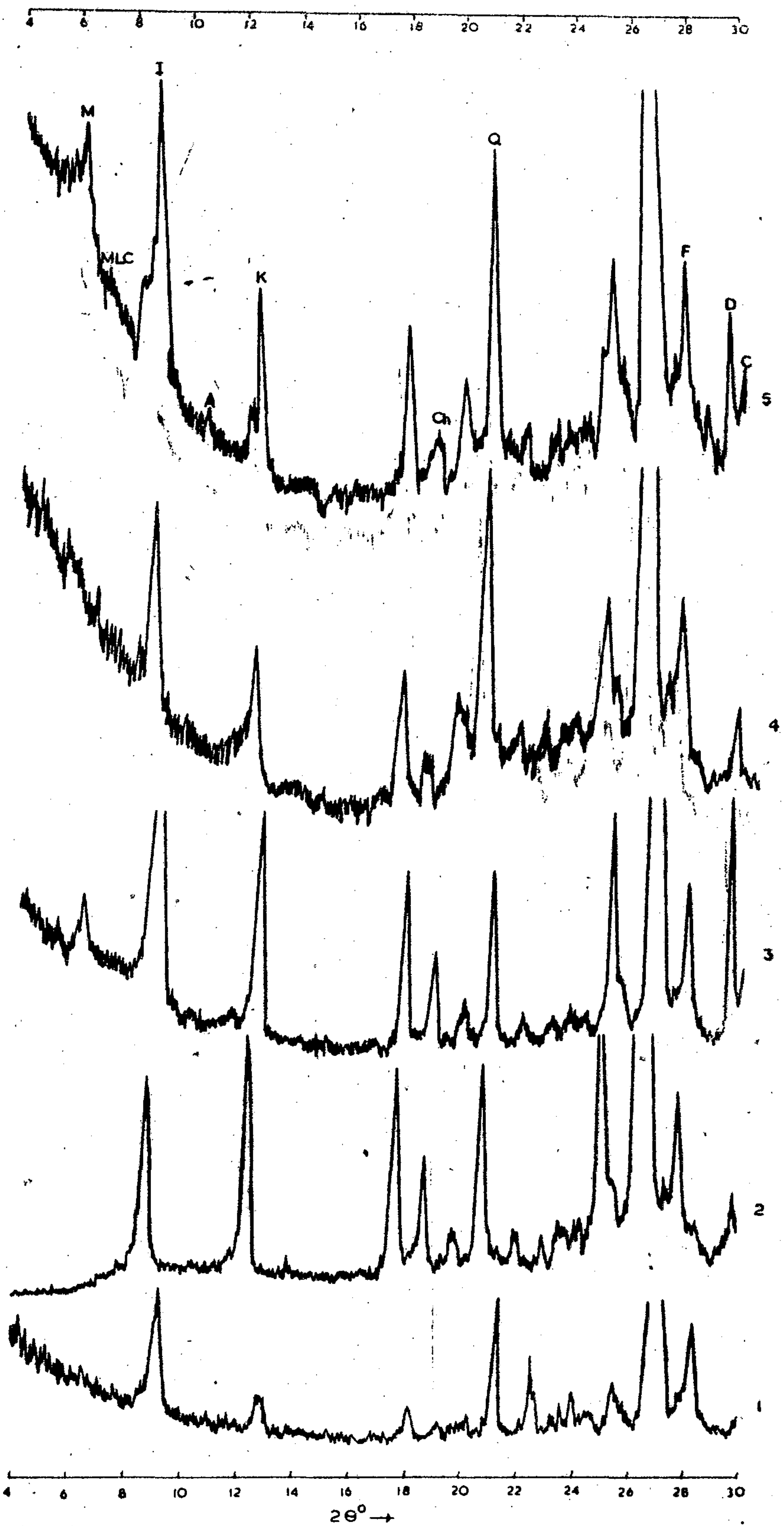

FiG 5.8 X-ray diffractographs of suspended sediments from the Ganga 1,2, Hoogly 4; Gandak 3; & Son 5; D=Dolomite C=Calcite, F=Feldspar, Q=Quartz, Ch=Chlorite, K=Kaolinite, A=Amphibole I=Illite, MLC=Mixed Layerclays, M=Montmorilionite

Table 5.3: Mineralogy of the Suspended sediments of the Ganga River and its Tributaries

Name of the river and location	Percentage of various minerals									
	Dolomite	Calcite	Feldspar	Quartz	Chlorite	Kaolinite	Amphibole	Illite	MLC*	Montmorillonite
Ganga (Hardwar)	x	x	23.3	29.4	x	<1	1	33.0	3.4	2.2
Ganga (Kannanj)	<1	x	14.0	4.3	3.7	15.0	<1	57.0	2.0	5.0
Ramganga River	4.3	x	10.0	16.0	5.3	14.0	<1	43.0	<1	7.0
Yamuna River	x	12	6.0	44.0	x	23.0	2.5	4.0	Traces	10.0
Ganga (Allahabad)	1	x	21.0	18.3	13.0	33.0	x	14.3	x	x
Ganga (Ghazipur)	3.8	x	15.0	18.0	2.4	22.0	<1	32.0	1.4	5.5
Gomti River	0.4	<1	14.0	17.0	3.0	13.4	<1	50.0	<1	<1
Ghaghra River	1.6	5	6.0	57.0	3.0	11.0	<1	16.2	<1	<1
Ganga (Sonpur)	x	35	13.0	18.0	2.0	9.0	1	19.3	2.0	<1
Son River	<1	4.3	13.0	18.0	9.3	13.0	<1	36.4	2.0	3.4
Ganga (Patna)	x	5.0	7.0	24.0	2.3	17.5	<1	43.0	1.0	1
Gandak River	7.0	x	5.0	8.4	4.3	12.4	<1	60.6	x	2.3
Ganga (Farrakka)	1.7	1.3	11.0	22.0	4.0	24.0	<1	34.2	Traces	1.1
Hoogly (Calcutta)	3.0	x	23.0	28.0	3.0	14.0	<1	23.2	Traces	1

*MLC = Mixed Layer Clays.

parts of the basin, but also receives some tributaries in lower parts of the basin, draining Deccan Traps and other basic rocks. It has a mixture of high relief and low relief with basic igneous rocks. It shows low felspar because of their distruction during chemical weathering and high quartz because of their resistance to alteration.

Clay Minerals: In general, clay minerals are more abundant in low relief environment than the high relief environment because they are the product of low relief chemical weathering. This holds true for the Ganga River also.

The primary clay minerals are kaolinite and chlorite as it is evident from the stability diagrams. The other clay minerals are montmorillonite and illite as suspended clastic sediments. The lack of kaolinite at Hardwar and abundance in low relief environment proves the breakdown of silicates to form kaolinite in lower relief environment. Chlorite is present almost constantly except in mountaneous environment. The chlorite is present mostly as detrital grains but not as a primary clay mineral though the possibility of

Mg-chlorite is indicated in Fig. 5.7 D. The precipitation of chlorite is possible in marine sediments. Montmorillonite and illite are present in almost all the samples and have inverse relationship between their abundance.

Mixed layer clays are present in very small amount in all the samples, in which montmorillonite and illite are present showing anintermediate composition between the two.

Since no size separation was done for the suspended matter, the various proportions of clay minerals in the bulk sample may only be an approximation. To get a clear picture of the clay minerals, the size separation is important. Any mineral present as less than 10% of the bulk is not precisely detected in X-ray diffractographs.

Chemical and Sediment Mass Transport Calculations:

The chemical and sediment mass transport are calculated for the six tributaries sub-basin and also for the basin divided into various segments. These segments are the basin area from source to Hardwar, source to Kannauj and so on upto Calcutta. The results are listed in Table 5.6 and 5.7. Table 5.4 and 5.5

Table 5.4: Average elevation, basin area and annual average discharge of tributaries of the Ganga.

Sub-Basin Rivers	Average elevation* (meters)	Basin Area** (Km^2)	Annual Average Discharge* (million cubic meters)
Ramganga	1172	32,493	15,258
Yamuna	1206	366,223	93,020
Gomti	150	30,437	7,390
Ghaghara	1196	127,950	94,400
Son	325	71,259	31,800
Gandak	1383	64,300	52,200

* Calculated from Survey of India Map.

**From Rao (1975).

Table 5.5: Average basin elevation, basin area and annual average discharge of various segments of the Ganga River Basin

Basin upto:	Average basin* elevation (meters)	Basin area** (Km^2)	Annual Average Discharge*** (million cubic meters)
Hardwar	2453	95522	23900
Kannauj	1812	240510	39520
Allahabad	1509	358207	152000
Farakka	1260	648185	459040
Calcutta	915	750530	493400

* Calculated from Survey of India Map.

** Calculated approximately

*** From Rao (1975).

Table 5.6: Sediment and Chemical load in various sub-basins of the Ganga River Basin.

River sub-basin	Annual sediment load	Annual chemical load	Total annual load	Annual sediment erosion rate	Annual chemical erosion rate	Annual erosion rate	Sediment/chemical ratio	Decrease in mean elevation (mm/100 year)	Time required to reduce the basin to base level (10^6 years)
	--------10^6 metric/tons			-------Metric tons/km^2----					
Ramganga	10	2	12	337	87	424	3.87	17	6.9
Yamuna	125	17	143	343	49	392	7.0	16	7.7
Gomti	6	1	7	225	40	265	5.6	11	1.4
Ghaghra	125	16	141	978	130	1108	7.5	44	2.7
Son	50	6	56	709	96	805	7.38	32	1.0
Gandak	24	9	33	383	140	523	2.7	21	6.61

Table 5.7: Sediment and Chemical Load of the Ganga River Basin

Basin segment from sources upto various places listed	Annual sediment load	Annual chemical load	Total annual load	Annual sediment erosion rate	Annual chemical erosion rate	Annual erosion rate	Sediment chemical ratio	Decrease in mean elevation (mm/100 year)	Time required to reduce the basin to base level (10^6 years)
	------10^6 metric tons------			-----Metric tons/km^2-----					
Hardwar	14	2	16	152	26	178	5.8	7.0	30.4
Kannauj	15	6	21	64	27	91	2.3	4.0	50.0
Allahabad	228	28	256	639	79	718	8.0	29.0	5.3
Farakka	729	71.6	1045	1125	110	1235	10.2	29.4	3.0
Calcutta	328	83	411	438	111	549	3.9	22.0	4.2

enlist the average basin elevation, basin area and annual discharge.

The following formula were used to calculate these figures

$$ASL = Q \times TSM$$

$$ACL = Q \times TDS$$

where, ASL = Annual sediment load in metric tons.

ACL = Annual chemical load in metric tons.

Q = Discharge in million cubic meter/year.

TSM = Total suspended matter in ppm

TDS = Total dissolved solids in ppm.

Calculation of time required to reach the basin elevation to base level: For calculating the total time required to reduce the basin to base level, the mass of the basin is calculated by following formulae and then divided by the annual erosion rate in metric tons.

$$M = A \times 10^6 \times H \times \sigma \text{ metric tons}$$

where, M = Mass of the basin in metric tons

A = Area of the basin in Km^2

H = Height in meters

σ = Density ($2.5\ g/cm^3$)

Calculation of annual decrease in elevation: It is calculated by calculating the thickness of the thin sheet of sediment which would be eroded by x Kg annual erosion rate.

$$\text{Erosion rate} = x\ \text{Kg/Km}^2\text{/year}$$
$$= x\ \text{Kg}/10^6\text{m}^2\text{/year}$$
$$= \frac{x\ \text{Kg}/10^6\text{m}^2\text{/year}}{2.5\ \text{Kg/m}^3} = \text{m/year.}$$

Mass transfer: Table 5.4 and 5.5 enlist average basin elevation basin area and annual average discharge for various tributary sub-sasins and in the basin at various places mentioned in the table. The mass transport (sediment + dissolved) are calculated for the same and listed in table 5.6 and 7.5. All these calculations are based on the samples collected during monsoon. Since river transport most of its load during monsoon period these values are taken as annual average. It has been pointed out by Subramanian and d'Anglejan (1976) that TSM transported by a river does not neccessarily reflect the total sediment transfer to the ocean because of the organic component of TSM ranging 30-50% of it. The bed load is also not monitored. So these calculations are approximate and give an insight into the mass transfer of the basin.

Sediment Mass transfer: Taking the Calcutta as a monitoring station for mass transfer, the Ganga River is annually discharging 328 million tons of sediment into the Bay of Bengal. This is second highest for the Indian rivers, the first being the Brahmaputra (Table 5.8), transporting 711 million tons of sediments annually to the Bay of Bengal. It contribute 30% of the sediment load from India. The sediment load of the Ganga is comparable with that of the Colorado, Mississippi and Irrawady and is aboutone third of Mekong and one fifth of Huang Ho (Table 5.9).

Chemical mass transfer: The Ganga River transports 83 million tons of dissolved load annually. This constitutes about 36% of the India's annual chemical load to the ocean. This is highest for India and can be compared with the Congo. This is about one third of the Amazon and is about less than half of the Mississippi. The chemical load of the Ganga alone is more than the total chemical load of Australia transported annually. This is about 2.1% of chemical load of the continental earth. This is evident that the Ganga river is chemically very active and as compared to its basin area, it is contributing enormous dissolved minerals into the ocean.

Table 5.8: Denudation rates for Major Indian Rivers*
(other than Ganges)

Basin	Chemical load	Sediment load	Total load	Chemical rate	Sediment rate	Total denudation	Sediment/Chemical ratio
	----10^9 kg/km^2/yr -----			---10^4 Kg/Km^2/yr------			
Kauvery	7.6	0.71	8.3	8.7	0.87	9.57	0.1
Krishna	15.0	8.50	23.5	6.1	3.41	9.42	0.5
Godavari	22.0	16.20	38.2	7.3	5.30	12.60	0.7
Narmada	11.0	6.20	17.2	12.1	7.00	19.10	0.5
Tapti	5.3	2.70	8.0	8.7	4.30	13.0	0.4
Mahanadi	8.4	7.10	15.5	6.4	5.40	11.80	0.8
Brahmaputra	81.0	711.20	792.2	12.2	110.11	122.31	9.0

*Subramanian (1978).

Table 5.9: Erosion rates of Some important rivers in the World*

River	Chemical load	Sediment load	Total load	Chemical rate	Sediment rate	Erosion rate
	---10^9 kg/year			----10^4 kg/km^2/year----		
Amazon	232	499	731.0	3.68	7.92	11.66
Congo	98.5	31	129.5	2.54	8.0	3.34
Mississippi	118.0	213	331.0	3.66	6.61	10.27
Colorado	17.29	297.79	315.08	2.55	46.7	49.25
Columbia	40.74	31.24	71.98	6.39	4.9	11.29
Ob	29.60	14.2	43.8	1.22	0.6	1.82
Yenesei	30.90	10.5	41.4	1.14	0.4	1.54
Mekong	60.6	1000.0	1060.6	7.50	120.0	127.50
Huang Ho		1610.8	-	-	215.0	-
Irrawady		300.0	-	-	69.8	-
Indus	45.9	400.0	445.9	4.95	42.6	46.95

*Data for Colorado and Columbia - recalculated from Judson (1961) and from Gibbs (1972) respectively.

Total mass transfer: The total mass transfer of the Ganga River Basin is 411 millions tons annually. This is second highest for the Indian rivers. The Ganga River Basin having basin area 26% of India, contributes 31% of the India mass transfer to the adjacent oceans. This is little less than the Amazon, Indus and Brahmaputra, but is less than half of the Mekong.

Erosion rates: The total erosion rate for the Ganga River Basin is 549 metric tons/Km^2/year (438 sediment + 111 chemical load). This is about half the erosion rate of the Brahmaputra and is greater than any other Indian river. Compared to other big rivers of the world, this is less than half of the rate of Mekong but is higher than any other river of the world. Only the erosion rate of the Colorado can be compared with that of the Ganga.

The erosion rates in the Ganga River Basin are uncorrelated with the elevation. The Son having a mere elevation of 325 meters is having second highest erosion-rate (804 metric tons/Km^2/year) while Yamuna having much higher elevation (1349 m) has got only erosion rate 392 tons/Km^2/year. Ghaghra having a high elevation has got highest erosion rate.

Sediment/chemical erosion ratio: The ratio of sediment to chemical erosion is about 6 to 1 for the Ganga (present work) and 9 to 1 for Brahmaputra (Raymahashaya, 1970; Subramanian, 1978). For the Ganga, Subramanian and Dalavi (1978) reported the ratio of 6.3 to 1 and Raymahashaya (1970) reported 7 to 1. All the Himalayan rivers are having sediments to chemical erosion ratio more than 1, while all the rivers of peninsular India are having ratio less than 1. This shows that the Himalayan rivers are mechanically more active, while peninsular rivers are chemically more active. The ratio of the Ganga can be compared with the Indus. It is three times that of the Mississippi and the Amazon, but less than half of the Mekong, which has got the highest ratio.

In Fig. 5.9, the chemical erosion rates are plotted against the sediment erosion rates. It shows that there is an increase in chemical erosion rate with increase in sediment erosion rate. The data point of Yamuna falls far away from the line showing a very high chemical erosion rate as compared to its sediment erosion rate. Because of the high chemical erosion rate, mainly controlled by rock type in the tributaries like the Betwa, Chambal, etc. the Yamuna has high chemical erosion rate.

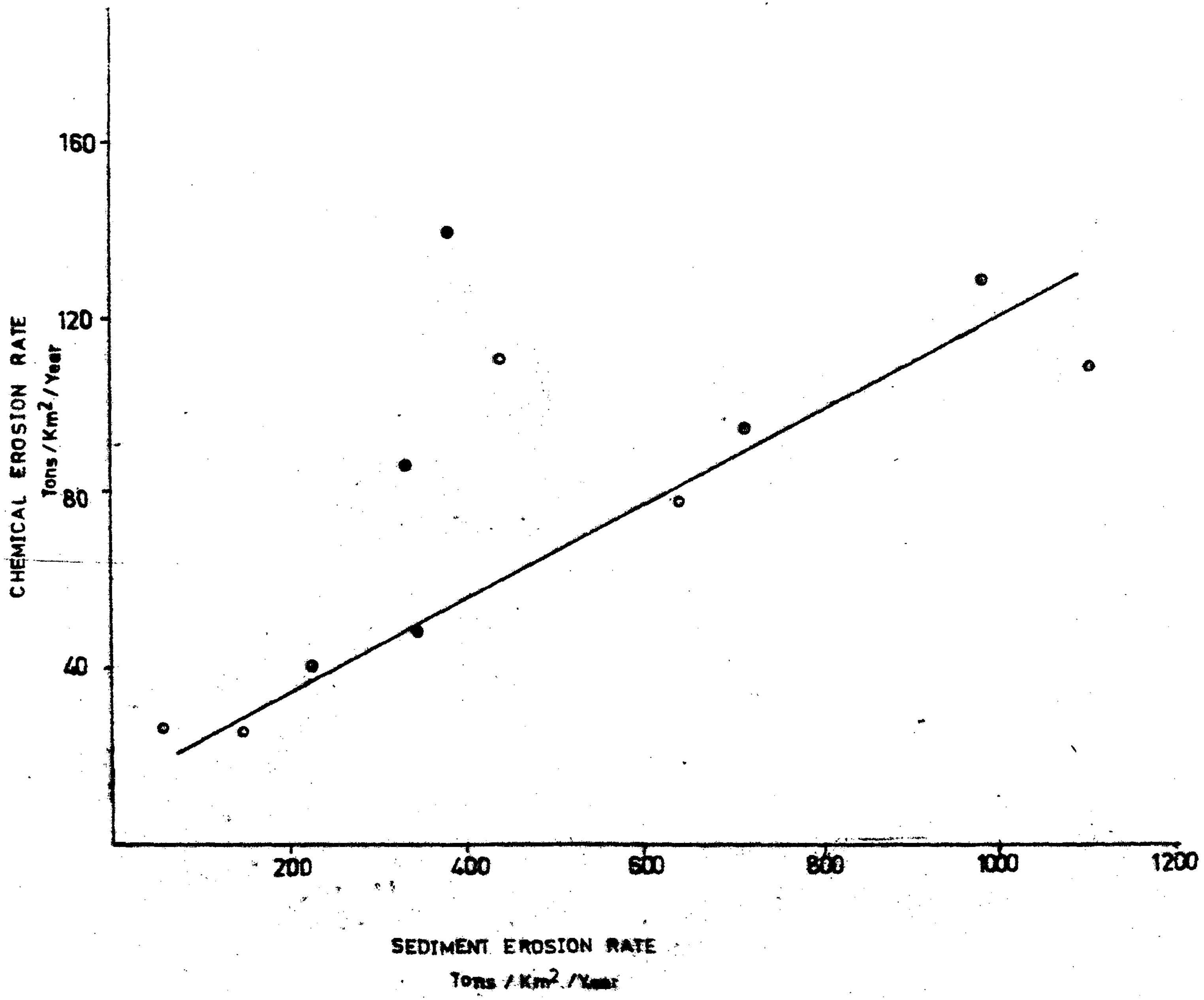

Fig. 5.9: Showing increase chemical erosion rate with increase in sediment erosion rate.

In Fig. 5.10, the data for erosion rates are plotted against the basin area. In graph A the data point are for the tributary basins and in B, the values are at various points in the main river basin. Plot A shows a clear positive correlation with the basin area. This is on contrary to the observation made by Subramanian (1982) for the Krishna River. Basin. Plot B also shows the initial increase in erosion rate with increase in basin area, but at very large basin area, the erosion rate almost becomes constant.

Thus, it is evident that the erosion rates are not governed mainly by relief as it is in the Amazon but also by basin area, rock type (as shown by TSM values) discharge (not discussed here), climate etc.

<u>Basin elevation changes</u>: Based on erosion rate and the average basin elevation the decrease in mean elevation/ 100 years and total required time to reduce the basin to base level is calculated and listed in table 5.6 and 5.7. On the average, the Ganga River Basin would be reduced to mean sea level in 4.2 million years. This is higher than 3.6 million years reported by Subramanian (1978). Some of the sub-basin which are having high erosion rate or low elevation as the Son and Gomti would be reduced before the others and hence, the

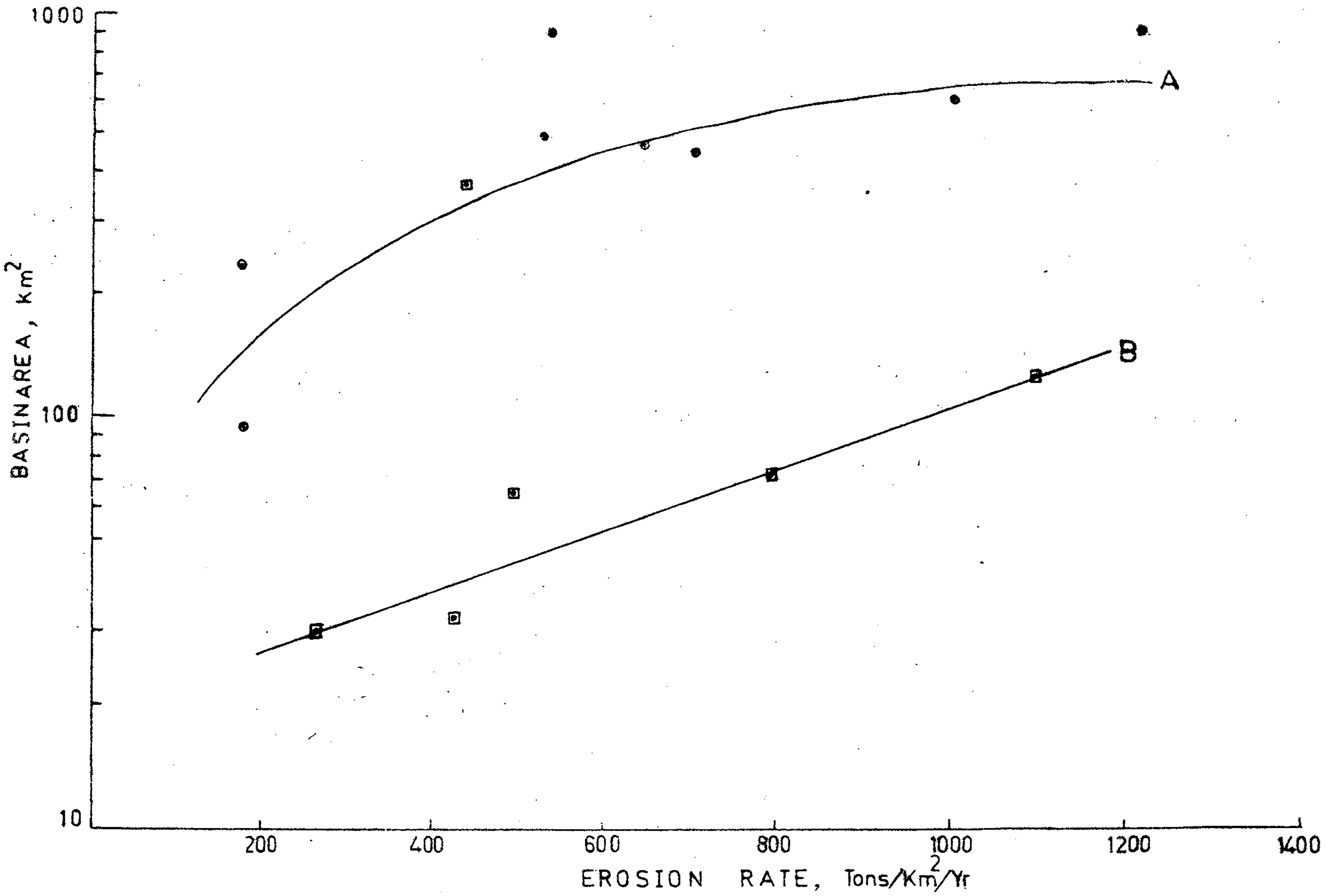

Figure 5.10: Showing increase in erosion rate with increasing basin area
A= Points at various places in the basin;
B= Points of tributary basins.

sediment supply from that basin will be cut off resulting a decrease in erosion rate. This is also subject to no continental uplift in future.

Gibbs (1981) reported that 3406 years would be required to fill the shelf region of the Ganga at present denudation rate. If this is true, then the whole land will be flooded with sea water before the time to reduce the basin to sea level is reached.

CHAPTER VI

CONCLUSION

From the preceding discussions, it is concluded that the Ganga River water is alkaline as most other rivers of the world. There is a control of rock type and recycling of constituents on the river water chemistry. The river water is undersaturated with respect to quartz and amorphous silica and is in equilibrium with dolomite, kaolinite and chlorite. The salinity generally increases downstream but there is a general decrease in suspended solid concentration downstream. The kaolinite, illite, chlorite, dolomite, calcite, quartz and feldspar are the dominant constituents of suspended sediments. Kaolinite and calcite are the primary chemical precipitates while illite, chlorite, dolomite, quartz and feldspar are the detrital material present in the suspended sediments. The mineralogy of suspended matter is controlled by rock type and type of weathering process operating in catchment area. The total mass transfer by the river is among top five rivers of the world and with its present rate of mass transfer (412 million metric tons/year), it would require about 3000 years to fill the shelf region of the Bay of

Bengal (Gibbs, 1981). The Ganga is eroding the continent at very high rate (549.5 metric tons/Km^2/year) and would require about 4 million years to reduce the basin elevation to mean sea level, provided there is no significant change in continental elevation by uplift.

It is quite interesting to look into the long term implications of the sediment erosion, deposition and redistribution in cycling of the rocks. The sediments are continuously deposited containing a mixture of detrital material, biochemical and chemical precipitates and authigenic minerals. These sediments undergo diagenosis after burial. About 20% of this total total mass is lost during post-depositional processes by solution. At the same time, subducted and compacted sediments are raised above sea level, weathered and eroded again to give rise to new sediments. The rocks which remain, become older and older with time and are attacked by agents of removal and distruction. The ratio of various rock types change through time because of selective removal and high cycling rates of those which are susceptible to dissolution such as carbonate and evaporites. The average composition of the sedimentary rocks in the geological past have been the same as that observed today (Garrels,and Mackenzie, 1972).

The mass of the post-Precambrian sediment is 18000 x 10^{20} g, which were deposited during last 600 million years that is the age during which there has been no significant change in the chemistry of ocean water. The rate of deposition for this mass would be 30 x 10^{14} g/year (Garrels and Mackenzie, 1971). But the present rate of flux is 250 x 10^{14} g/year. Thus, today's rates of erosion hence deposition are much higher than the average rate calculated for the geological past. There has been high deposit rates in the past also. Gregor (1968) has shown that for the Tertiary period, the existing sedimentary mass corresponds to an annual sediment flux of about 50 x 10^{14} g/year, whereas, the rate over Pleistocene and Recent is about 100 x 10^{14} g/year. There are time intervals in which the thickness of the sediments preserved are much higher than in others and they are interpreted in stratigraphy as the periods of prolong sedimentation as Gondwanas. But it may not be true. This may be simply because of higher erosion rates in those periods. The other reason may be that the sediments were deposited in deep basins and enough sediment was accumulated before they were recycled on the land. The small preserved mass in the stratigraphic column may be a period of low deposition or a period of high selective destruction.

The transgression recorded in the geological past may be just a reflection of high accumulation of sediments on the sea floor and consequent transgression of the sea. The Bay of Bengal at present is receiving enormous sediment flux and is probably preparing for a transgression in next 3000 years before a base level erosion is reached.

The present study of the geochemistry of the Ganga River Basin, apart from aspects of erosion, highlights the total sediments and chemical mass transfer, mineralogy of the sediment flux and chemical quality of the river water. Thus, it deals with a part of the geochemical cycle of sedimentary rocks essentially made up of different elements. Hence, a more intensive study may be useful in understanding the geochemical cycle of elements in the sedimentary processes.

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