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# **NATURE OF CHEMICAL AND SEDIMENT LOAD IN THE MAHANADI 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**

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**1988**

## THE RIVER

At the feet of that blue sky, on the whitesnow,  
the river sleeps under the cover of soft clouds,  
and wakes up with the touch of warm sun.  
She slowly ventures out through the mountains and forests.  
Dancing, pushing and playing with the boulders and pebbles,  
she ultimately comes down to the soft land of the plains.  
The more she covers the length, the more she swells up in youth.  
At the land's end she ends her journey too,  
to remain eternally in the fathomless affection of sea.

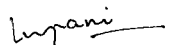


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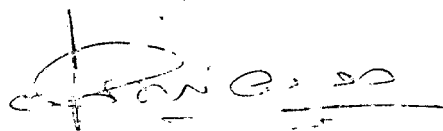
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C E R T I F I C A T E

The research work embodied in this dissertation entitled " NATURE OF CHEMICAL AND SEDIMENT LOAD IN THE MAHANADI RIVER BASIN " has been carried out in the School of Environmental Sciences, Jawaharlal Nehru University , New Delhi. The work is original and has not been submitted in part or full for any other degree or diploma of any University.



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## ACKNOWLEDGEMENT

It would be my pleasure if the words inscribed here could express, the amount of gratitude and indebtedness, I owe to my teacher, mentor and guide Prof. V. Subramanian. His immaculate guidance and constant encouragement through out this work has left an indelible impression upon me. I Thank him with much deference. The Dean, SES in thanked for providing the necessary facilities. I am thankful to Mr. S.M. Ali, Exe. Eng. central water commission. Hyderabad and Mr. A.K. Harit, Dy. Dir. Central Soil and Material Research Station, New Delhi for providing the discharge data of Mahanadi river. The otherwise gruelling field trip was made very pleasant by my cousins, Babu, Guru and Simabhai. Dr. Bheemalingeswara spared a lot of time in the analysis of my samples and providing with some very useful data. The Thesis would not have come to its final shape, but for the help rendered by my friends Choubey, Dasgupta, Dhanpal, Ghosh, Kanu, Manoj, Manoharan, Rama, Rath, Shailendra, Sukumar, Vaidya and Vijaypal to name a few and are duely acknowledged. Lastly, I thank Mr. Morris for giving the final touches in getting the thesis into its present shape.

G. J. Chakrapani

.....To Amma, Nanna and Visu

& Mohan

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## ABSTRACT

Thirty four samples of water, suspended and bed sediments were collected for two seasons (Dec' 86 and Aug-Sept. 87), at selected locations of Mahanadi river and its tributaries. Seasonal and downstream variations in the water chemistry were studied. Mahanadi river shows a higher bicarbonate content, reflecting the intense chemical weathering taking place in the basin. From the water chemistry, the aluminosilicate and carbonate minerals expected to be in equilibrium with Mahanadi river water were calculated. From the XRD studies, these minerals were also observed in the suspended and bed sediments. Based on the run-off data and sediment load data from the CWC for thirteen stations and combining these with present data of two seasons, the discharge weighted mean composition, individual elemental fluxes and erosion rates were calculated. Ninety five percent of the discharge is in the monsoon season, which controls the chemical composition of the Mahanadi river. Annually, Mahanadi delivers 11.56 million tonnes of load to the Bay of Bengal. The ratio of dissolved to sediment transport is four. Factors controlling the erosion rates are discussed. The erosion rate is controlled by the basin area and elevation. The Mahanadi basin lowers at a rate of 1.59 mm per year. The suspended and bed sediment size distribution were studied and various statistical parameters determined. The mineralogy of bulk suspended and bed sediments show the predominance of kaolinite, montmorillonite and illite in the clay minerals.

## INTRODUCTION

Rivers are the representatives of the present-day geochemical processes involving constant mobility of materials such as water, sediments and dissolved salts to the oceans. The physico-chemical processes which are responsible for the mobility of the materials in the present day environment might have been operated through out the geological past, though not necessarily with the same intensity. Rivers and lakes with a total mass of  $0.3 \times 10^{20}$  g make up 0.002% of the total hydrosphere. Although the total amount of these terrestrial waters is insignificant in comparison to the mass of the hydrosphere, these waters are important geochemically, because they are responsible for most of the weathering and erosion of the landmasses.

The two fundamental processes of weathering -mechanical and chemical- result in suspended and dissolved loads of rivers, which represent quantitatively the most important input to the oceans (Holland, 1978). It is estimated that annually about 37,000  $\text{Km}^3$  of water and  $13.5 \times 10^9$  T of sediments are discharged by the rivers to the oceans (Milliman and Meade, 1983). The components which are not very mobile, such as silica, aluminium, iron, titanium and potassium are mainly exported by mechanical erosion processes, whereas calcium, magnesium, sodium and carbonates are removed from the basin primarily by chemical erosion (Probst, 1986). The river and stream borne soluble and suspended loads get affected in estuaries where there is continuous mixing between fresh water and sea water (Evans et al., 1977, Fukai et

al,1973, Krishnaswamy,1976, Sholkovitz,1976, Turekian, 1971,1977) by processes such as flocculation, adsorption-desorption, recycling through biologic processes etc. The chemical composition of the eroded matter depends on the mean composition of the materials lifted above sea level, on the relative effectiveness of chemical weathering compared to physical weathering, and on the response of the uplifted materials to the chemistry of the atmosphere (Garrels and Mackenzie,1971). Subramanian (1979) estimated that at the present rate of erosion, with no compensating uplifting mechanism, river basins in India would achieve their base level of erosion in 5 million years.

A stream will transport sediment only if the critical hydraulic condition is exceeded. The critical stage is reached when the transporting capacity of a stream equals that which is required to dislodge material from the channel margin. Several attempts have recently been made to understand river transport of materials. The pioneer workers include Gibbs (1977), Martin and Meybeck (1979), Milliman and Meade (1983). Milliman and Meade (1983), estimated that nearly 30 % of transport of sediments by world rivers take place in the Indian sub-continent. To understand the geochemical mass balance between land and ocean, the estimation of mass transfer from continent to ocean, is very important. Since rivers are by far the most important supplier of material to the ocean system, several attempts have been made to understand river transport of materials. The important of these are by Gibbs (1977), Meybeck (1976), Milliman and Meade (1983), Martin and Meybeck (1979). Asian rivers contribute more than 70 %

of the global sediment input to the world oceans (Milliman and Meade,1983). In the Indian subcontinent , mass transfer studies have been initiated by Biksham and Subramanian (1980), Jha and Subramanian (1986), Ramesh and Subramanian (1985), Raymahasay (1970), Subramanian (1978,1979) and others.

Textural, mineralogical and chemical studies on riverine sediments offer an insight into river basin provenance and the effect of transport on the original relationship in the geological formations. The clay minerals of river suspensions reflect in general the geological setting of the respective drainage area. Large rivers with a heterogenous geology in their catchment basins show a great variability in the clay mineral composition of their suspended load.

There is an enormous effect of human activity on weathering and erosion processes as a result of ploughing agricultural fields, deforestation, acid precipitation and all types of engineering works on the earth's surface. Contemporary society has realised that an understanding of our environmental surroundings is of vital importance for the repair of prior degradation and development of future strategies (Pagenkopf, 1976). This awareness has led to a rapid increase in the number of studies involving the various aspects of natural water chemistry.

## LITERATURE REVIEW

The hydrologic cycle is an important contribution to near-surface chemical processes. Approximately 80 % of the water on the earth is in the oceans, 19 % is in the pores of rocks beneath the earth surface, 1 % is in the form of ice, 0.002 % is in streams and lakes and only about 0.0008 % in the atmosphere (Garrels and Mackenzie, 1971). Although rivers and lakes make up only a small fraction of the hydrosphere, the rate of water circulation through them is quite rapid. Garrels and Mackenzie (1971) calculated that the amount of water discharging from rivers to the sea each year is about equal to the total amount of water present in rivers and lakes.

I.1. Sediment and Chemical Load of Rivers

On the basis of 40 major world rivers, Meybeck (1976) estimated that the annual global dissolved transport to world oceans is 3.25 billion tonnes. Milliman and Meade (1983), computed the solid material transport to the world oceans to be around 13.5 billion tonnes per year. The amount of material transported to the oceans by rivers depend on the size of river basins, their homogeneity and the range of morphoclimatic features (Meybeck ,1976). Most of the studies on world rivers show that solid transport is directly related to run-off, altitude , precipitation, relief, temperature and inversely related to basin-size and vegetation. Table I.2 lists the major rivers that flow to the sea in order of discharge.

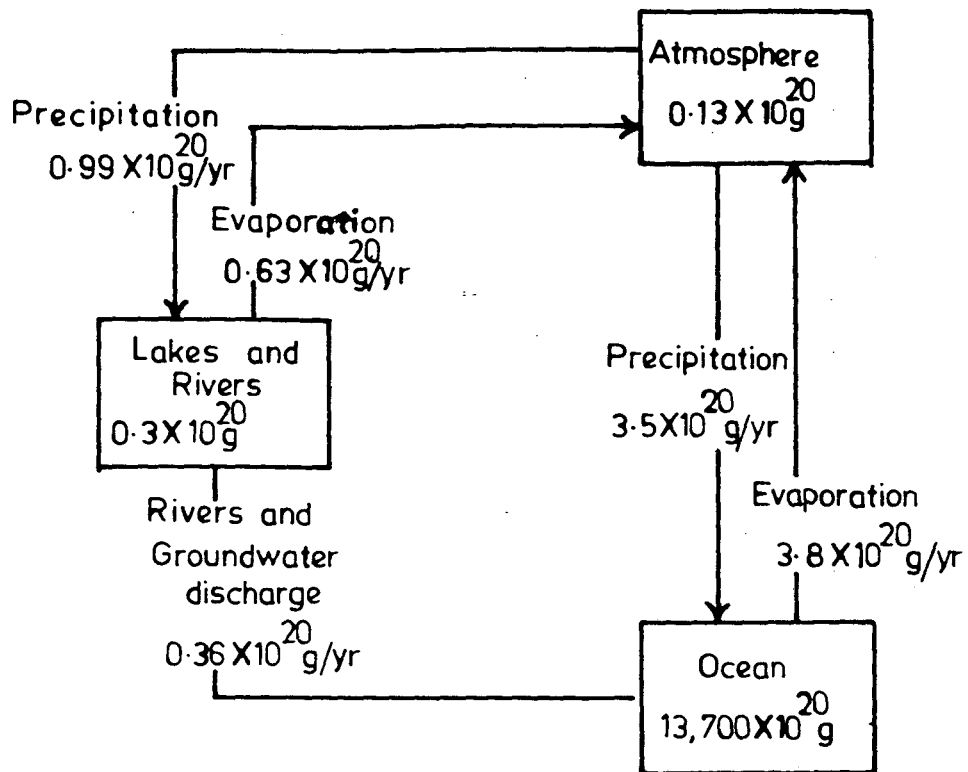


Figure I.1: Schematic diagram for the hydrologic cycle.  
Drever, 1982.

Table I.1

Average suspended sediment discharge by continents.

Continents	Suspended sediments (t/km <sup>2</sup> /yr)	discharge (10 T/yr)
Africa	27	0.55
Asia	600	16.16
Australia	45	0.23
Europe	35	0.33
North America	96	1.99
South America	63	1.22

Gregory and Walling (1973)

Table I.2

Major rivers that flow to the sea, listed in order of discharge.

River	Location	Annual Discharge			diss./sus.	Drainage area ( $10^6$ km <sup>2</sup> )
		water (km <sup>3</sup> /yr)	diss. solids ( $10^6$ t/yr)	sus. solids ( $10^6$ t/yr)		
Amazon	S. America	6300	223	900	0.25	6.15
Zaire	Africa	1250	36	43	0.84	3.82
Orinoco	S. America	1100	39	210	0.19	0.99
Yangtze	Asia	900	226	478	0.47	1.94
Brahmaputra	Asia	603	61			0.58
Mississippi	N. America	580	125	210	0.60	3.27
Yenisie	Asia	560	65	13	5.0	2.8
Lena	Asia	514	70	12	5.8	2.50
Mekong	Asia	470	70	160	0.44	0.79
La Plata	S. America	470	16	92	0.17	2.83
Ganges	Asia	450	75			0.97
Irrawady	Asia	428	92	265	0.35	0.43
St. Lawrence	N. America	447	59	4	14.8	1.03
Mackenzie	N. America	306	64	100	0.64	1.81
Columbia	N. America	251	35	8	4.4	0.67
Indus	Asia	238	41	100	0.41	0.97

Berner and Berner, 1987.



The first 13 rivers with a total discharge of 14,000 km<sup>3</sup> water per year, account for about 38 % of the total water discharge to the oceans. Amazon accounts for 17 % of the total water discharge to the oceans. Seventy percent of the total world suspended load is from southern Asia (Milliman and Meade, 1983). The total suspended sediment load can be used to calculate the average mechanical denudation rate for the continents, which is about 5.6 cm. of elevation reduction in 1000 years. Milliman and Meade (1983) pointed out that the sediment transport rate from the continents to the oceans by the rivers is not the same as the total rate of soil erosion. This is because much sediment is eroded from upland areas and deposited in lowland areas without reaching the sea.

## I.2 Review of Indian Rivers

Arranged according to drainage area, the nine major river basins of India are the Indus, Ganges, Brahamaputra, Godavari, Krishna, Mahanadi, Narmada and Cauvery. Together with 40 minor rivers, the water discharge from the Indian sub-continent is about  $1700 \times 10^{19} \text{ m}^3/\text{yr}$ , which represents just 5 % of the global river input to the world oceans. Unlike the large river system of Amazon, representing a single drainage net-work the Indian rivers cover practically all climatological, geographical, geological and human factors and thus offer challenges to work with (Subramanian, 1987).

Table I.3

Erosion rates for the continents

Continent	Load ( $10^6$ t/yr)			Rate (t/km <sup>2</sup> /yr)		
	chemical	sediment	total	chemical	sediment	total
Asia	1490	14500	15990	32	302	334
Africa	710	490	1200	24	16	40
Europe	460	250	710	42	23	65
Australia	20	210	230	2	21	23
N.America	700	1780	2480	32	85	117
S.America	550	1100	1650	28	56	84
Continental earth	3930	18300	22230	23	108	131

Garrels and Mackenzie, 1971.

Table I.4

Hydrological characteristics of river basins of India

River	Mean annual discharge ( $10^9 \text{m}^3/\text{yr}$ )	Drainage area ( $10^3 \text{km}^2$ )	Mean basin elevation (m)	TDS (ppm)	TSM (ppm)
Ganges	493	970	3000	178	1631
Brahmaputra	510	690	5000	148	1170
Indus	207	1165	2500	124	450
Godavari	92	313	400	181	1845
Krishna	30	251	420	360	1158
Mahanadi*	67	132	500	155	31
Narmada	41	90	760	322	130
Cauvery	21	87	630	172	30
Tapti	18	62	740	322	333
Minor rivers	104	240	-	-	-

Subramanian,1987.\* as studied earlier

The river water chemistry and chemical transport studies on Indian rivers are rather scant. The Central Water and Power Commission has carried out partial analyses of water of the major Indian rivers over a period of years (e.g. Deb and Chadha, 1964), but their studies were oriented towards determination of the quality of the river waters for irrigation use. Handa (1972), studied the chemical composition of the Ganga river water. Preliminary and broad investigations have been periodically reported by Borole, Raymahasay, Sarin and Krishnaswamy, Somayajulu, Subramanian and others.

✓ Indian rivers are alkaline and carry a greater annual solute load than the Amazon but have a smaller annual solute flux than similar Chinese systems. Na and Cl transport in Indian rivers is higher than in other major river systems of the world, probably due to the influence of the monsoon on continental run-off (Subramanian, 1983). The Himalayan drainage system, consisting of the Ganges-Brahmaputra and Indus, contribute enormous quantities of sediments to the Bay of Bengal and Arabian sea.

The earliest published qualitative data of clay mineral assemblages of Indian continental shelf sediments were of Subba Rao (1963). Subsequently, a number of workers have studied the distribution of clay minerals in the continental margin and deep sea areas of the Bay of Bengal (Goldberg and Griffin, 1970; Mallik, 1967; Murthy and Srivastava, 1979; Rateev et al. 1969; Siddique, 1967; Venkataratnam and Biscaye, 1973;). The clay mineral groups in the Arabian sea were reported by Goldberg and

Table I.5

Average chemical composition of Indian rivers (in mg/l).

River	HCO <sub>3</sub>	Cl	SO <sub>4</sub>	SiO <sub>2</sub>	Ca	Mg	Na	K
Krishna	178	38	49	24	29	8.1	30	2.4
Cauvery	53.3	18	39	8.4	15.4	16	30	2.6
Godavari	105	17	9	10	22	5	12	3
Ganges	100	5.6	9.4	3.1	40.5	6	8.7	3.9
Brahmaputra	37.5	15	9.5	6.7	29	7.4	12	2.5
Indus	64	9.2	15	5.3	26.8	0.7	1.3	2.1
Narmada	225	20	5	9	14	20	27	2
Tapti	150	65	0.6	16	19	22	47.5	3

Subramanian, 1987.

Table 1.6

Erosion rates of some important rivers of India

River	Load ( million tonnes/yr)			Rate ( t/km <sup>2</sup> /yr )			Sed/Chem.
	Chem.	Sed.	Total	Chem.	Sed.	Total	
Krishna	10.4	4	14.4	41	16	57	0.39
Godavari	17	170	187	55	555	610	10
Cauvery	3.5	0.04	3.54	40	0.5	40.5	0.01
Brahmaputra	51	597	648	88	865	953	9.8
Ganges	84	329	413	111	438	549	3.9

Subramanian,1987

Griffin,1970; Kolla et al.1976,1981; Mattiat et al.1973; Nair et al.1982; Rateev et al.1969; Srivastava,1970. Naidu (1962), studied the clay mineral assemblages off Godavari river sediments. Later similar work was done by Seeralathan and Seetharamaswamy (1982,Cauvery), Subramanian (1980), Swamy et al.(1973,Krishna) and others on the Indian sub-continent on the whole.

### I.3 Objectives

The present work aims at examining the followings:

- 1.The variation of major ion chemistry with seasons.
- 2.The average chemical composition of Mahanadi river water.
- 3.Factors controlling the Mahanadi river water.
- 4.The theoretically expected stable minerals in carbonate and sillicate system in Mahanadi river water.
- 5.To know, whether the theoretically predicted mineral assemblages from the water chemistry, agree with that of the observed minerals in the suspended sediments.
- 6.The load and rate of chemical and sediment erosion in Mahanadi river. Calculation of flux of individual elements.
- 7.Grain size distribution of suspended and bed sediments.
- 8.Mineralogy of suspended and bed sediments.

## MAHANADI RIVER BASIN

The Indian sub-continent enjoys a unique position on the globe for its water resources. To the north of it lie the snow capped Himalayas, feeding the rivers emerging from them, one-fifth of their flow by snow-melts while in the south lie the Indian ocean, the stimulus zone of two important monsoons i.e. the south-west and north-east monsoons. The monsoons unleash enormous quantity of water which is carried by the numerous river systems flowing in all directions of the country. The complex topography of the sub-continent makes rainfall heavy in some areas while it is scanty elsewhere.

The Mahanadi is one of the major rivers of the country, flowing east and draining into the Bay of Bengal. Among the peninsular rivers in water potential and flood producing capacity, it ranks second to the Godavari. The Mahanadi basin extends over an area of about 1,13,717 sq. km. upto Kaimundi(delta head), and lies between longitude 80°-30' and 84°-50' east and latitude 19°-20' and 23°-35' north. The basin covers large areas in the states of Madhya Pradesh and Orissa and only small areas in Bihar and Maharastra. The state-wise distribution of drainage area of the river is given below :

State	Drainage area (sq. km.)
Madhya Pradesh	75,532
Orissa	55,754
Bihar	159
Mahrastra	279



The Mahanadi basin is bounded on the north by the central India hills and south-east by eastern ghats and on the west by the Mekala range. The upper basin is a saucer shaped depression known as Chattisgarh. The basin is in circular shape with a diameter of 400 km. and an exist passage of about 160 km. length and 16 km. breadth. Map of Mahanadi basin is given in Fig. II.1 .

There are four well defined physical regions in the basin, namely

1. The northern plateau
2. The eastern ghats
3. The coastal plains, and
4. The erosional plains of the central table land.
5. The northern plateau

The northern plateau and eastern ghats are well forested hilly regions. The coastal plains stretching over the districts of Cuttack and Puri covers the large delta formed by the Mahanadi and is a fertile area well suited for intensive cultivation. The coastal plains of the central table land area is traversed by the Mahanadi and its tributaries.

### II.1 River System

The Mahanadi river rises near Sihawa, which is near Nagri town in Raipur district of Madhya Pradesh. The total length of the river from the source to its outfall into sea is about 851 km. out of which, 357 km. is in Madhya Pradesh and the balance 494 km. is in Orissa. Throwing off numerous branches the Mahanadi falls into the Bay of Bengal near Flease Point about 16 km. below the confluence of Chitartala and the Mahanadi.

### II.1.1 Principal Tributaries

The principal tributaries of Mahanadi are the Jonk, the Hasdeo, the Mand, the Ib, the Ong and the Tel, which are briefly described below.

The Seonath : The Seonath sub-basin covers the districts of Rajnandgaon, Durg, Raipur, parts of Bastar and Mandla districts of Madhya Pradesh and Chandrapur districts of Maharashtra. From the source, at an elevation of about 533 m. near Kotgal in Chandrapur to its confluence with Mahanadi, Seonath traverses a distance of about 383 km. and drains an area of 30,761 sq. km. which is near about 25 % of the total catchment area of the Mahanadi basin. The main sub-tributaries joining the Seonath are the Kharkhara, the Tandula and the Kharun on the right bank and the Sukhanala, the Surhi, the Dotunala, the Hamp, the Agar, the Arpa, the maniyari and the Lilagar on the left bank.

The Jonk : The Jonk river rises in Khariar hills of Kalahandi district of Orissa at an elevation of about 762 m. The river flows for a length of about 196 m. and joins Mahanadi at Seorinarayan. It has a catchment area of 3483 sq. km. The sub-basin covers the districts of Kalahandi, Sambalpur and Raipur.

The Hasdeo : The Hasdeo river rises at an elevation of 915m. at a place nearly 10 km. north of Sonhat in the Surguja district of Madhya Pradesh and has a total length of 333 km. Its catchment area is 9802 sq. km. and the principal sub-tributary is the Gejnadi. The sub-basin covers areas in the districts of Surguja and Bilaspur.

Scale = 200 km

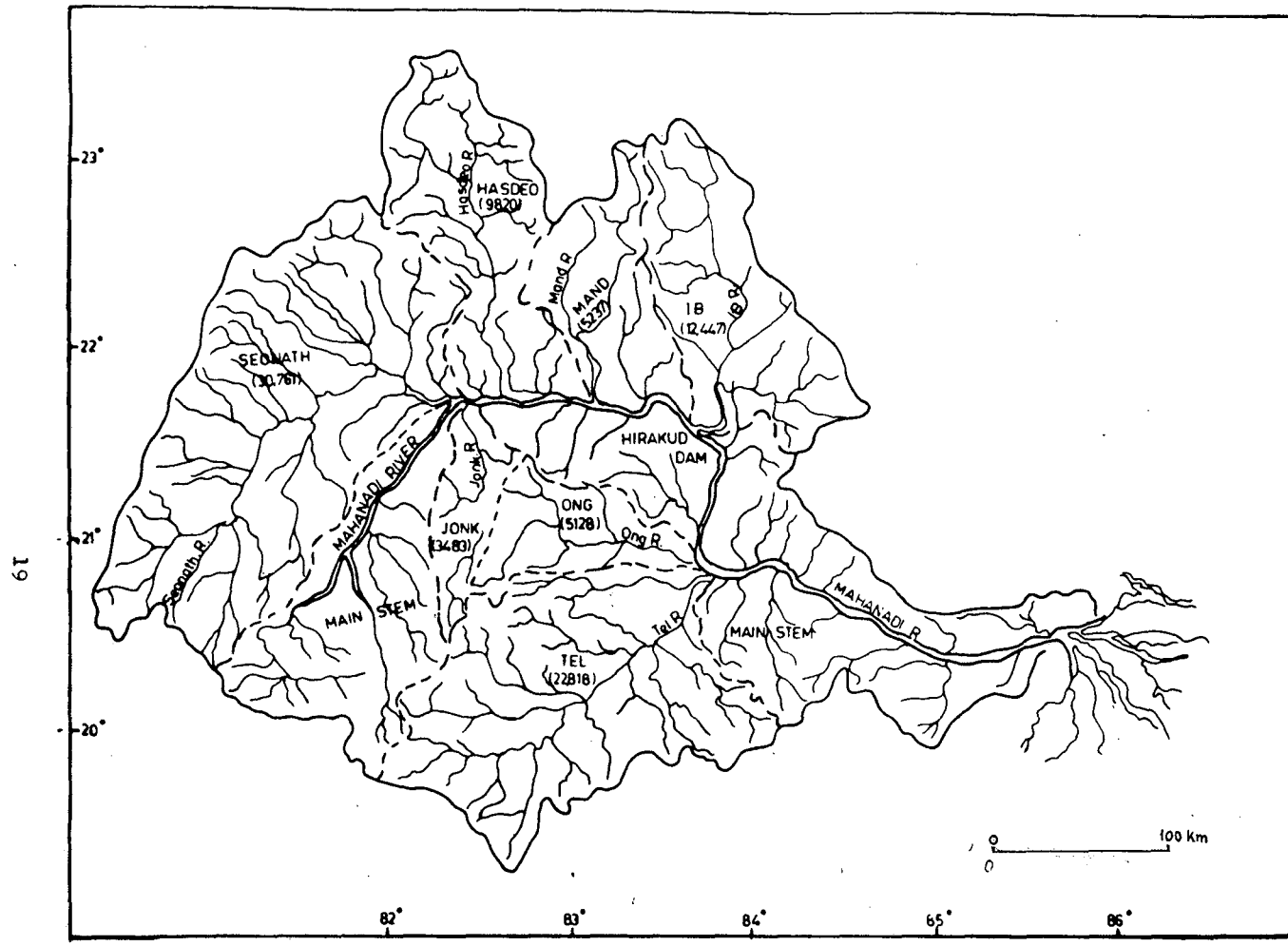


Figure II.1: Mahanadi river with its important tributaries and sub-basin areas (sq.km.).

The Mand : The Mand river rises in the Surguja district at an elevation of about 686 m. and flows for a length of about 242 km. upto its confluence with Mahanadi near Chandrapur. It has a catchment area of 5237 sq. km. The sub-basin covers the districts of Raigarh and Surguja.

The Ib : The Ib river is about 251 km. long and rises at an elevation of about 762 m. in the Raigarh district of Madhya Pradesh. The river traverses for about 251 km. before falling into the Hirakud reservoir and has a total catchment area of 12447 sq. km. The sub-basin covers districts of Raigarh, Sundargarh and Ranchi.

The Ong : The Ong river rises at an elevation of 457 m. on a hill in the northern outskirts of the south-north running range of mountains situated to the right of the Jonk river. The Ong flows for a total length of 204 km. to join the Mahanadi 11 km. above Sonapur. It has a total catchment area of 5128 sq. km.

The Tel : The Tel river rises in the Koraput district, Orissa about 32 km. to the west of Jangaon and flows for a total length of 296 km. before it joins the Mahanadi about 1.6 km. below Sonapur. The total catchment area of this sub-basin is 22818 sq. km.

## II.2 Geology

The rock formations that are prevalent in the Mahanadi basin in Madhya Pradesh belong to the following stratigraphical divisions :

Recent, Pleistocene  
Lower Eocene  
Upper Cretaceous  
Gondwanas

Alluvium and Laterite  
Deccan Trap  
Post-Gondwana intrusions  
Mahadeva Formation  
Panchet Formation  
Raniganj Formation  
Barakar Formation  
Talcher Formation  
Intrusive rocks in the  
Charnockites  
Iron Ore Group  
Gangpur Group



Cuddapahs  
Archeans

14-9-55  
The gneisses form a very widespread type of rock in Orissa. Some well defined areas of Sambalpur, Puri and Cuttack districts consist of the Gondwanas. Also a fairly large exposure of the upper Gondwana rocks occur in the Mahanadi basin just west of the delta. The Eastern Ghats through which the Mahanadi passes in Orissa state consist of rock types as khondalites, charnockites, leptynites, quartzites and minor basic granulites, gneisses, migmatites, anorthosites, granites and minor basic intrusives of Pre-Cambrian age. The Precambrian sedimentary rocks in the drainage basin are chiefly conglomerates, sandstones, quartzites, shales and limestones. the coastal tracts constituted by the deltaic alluvium of the river with littoral deposits. The older alluvium is found along the Tel sub-basin and in Bargarh sub-division of Sambalpur district.

In the upper reaches of the basin i.e. the Madhya Pradesh portion of the basin, the following lithological variations are seen (with their exposure in sq. km.):

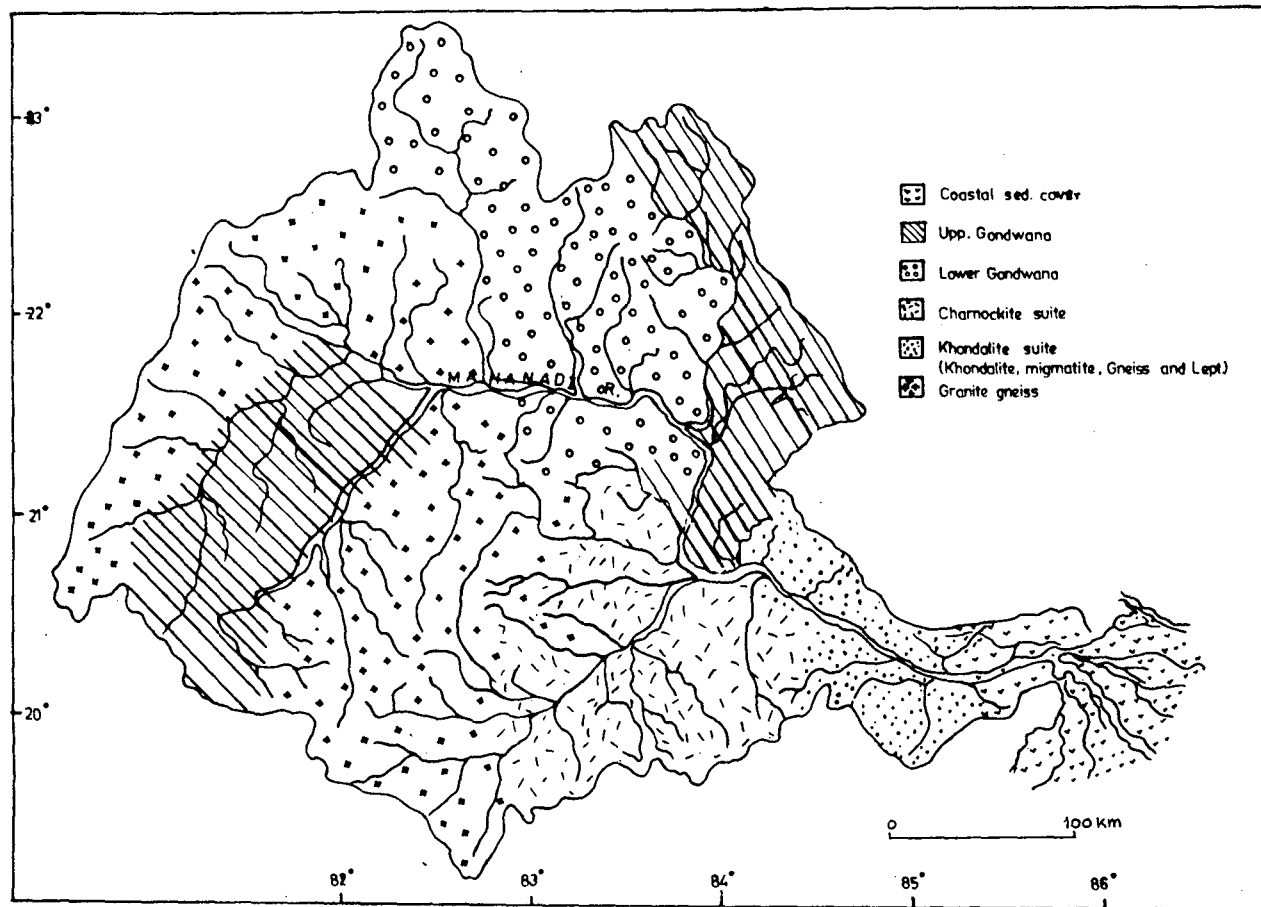


Figure II.2: Geological map of Mahanadi river basin. Compiled from GSI maps.

i. Granite and other crystallines.	83131
ii. Sand Stones	9523
iii. Lime Stones	15003
iv. Shales	5733
v. Gondwanas	11746

The Geological map of Mahanadi is given in Fig.II.2

### II. 3 Soil Pattern

The basin consists mainly of red and yellow soils, mixed red and black soils occur in parts of Bolangir, Kalahandi, Sambalpur and Sundargarh districts of Orissa. Laterite soil is found in the lower part of the basin lying in Cuttack and Puri districts of Orissa. The coastal plains of the Mahanadi are composed of saline deltaic soils.

The principal soil types found in the various districts of the basin are :

- i. Bastar, Rajnandgaon and Durg : The best soils of the districts are "Kanhar" and "Dorsa" both black and deep. "Kanhar" is a clayey soil containing about 43.3 to 56.5 %clay and 16 to 20 %of sand. "Dorsa" contain 37 to 44 % of clay, 25 to 29 % of silt and nearly 24 to 31 %of sand.
- ii. Bilaspur : The black soils prevail mainly in Mungali Tehsil where they cover 59 % of the area and the rest is entirely Dorsa.

- iii. Raigarh and Raipur : The main soils are Kanhar , Dorsa, Matasi and Bhata. Matasi is a yellow soil. Bhata is a red soil and full of stones.
- iv. Suruguja and Mandla : A mixture of red and yellow soils occur in these districts.
- v. Bolangir :The cultivated soils are loamy in texture, generally deficient in nitrogen and the nutrient contents are low.
- vi. Cuttack : the soils of the district vary from clays to clay-loams, the later being found to a greater extent.
- vii. Dhenkanal : Black soil or regular and old alluvium occurs. In general they have a higher content of clay.
- viii. Ganjam : Soils mixed with Laterite are found in this district.
- ix. Koraput : The soils are highly sandy.
- x. Kalahandi : Mixed red and black soils occur in the district.
- xi. Phulbani : Red and brown laterite soils occur in this district.
- xii. Puri : The soils are of sandy nature and are poor in plant nutrients.
- xiii. Sambalpur : The cultivable soils are loamy in texture and nutrient contents are low.



## II.4 Climate

Four distinct seasons occur in a year in the basin. They are :

- i. The cold weather,
- ii. The hot weather,
- iii. The south-west monsoon,
- iv. The post-monsoon season.

In the winter, the winds are generally light and blow either from north or north-east and the atmosphere is bright. During December and January, very little precipitation occurs, but during February 25 mm to 50 mm of rainfall occurs in association with the passing western disturbances. The precipitation is mostly confined in the northern half of the catchment especially the hilly region. The winter is not severe but pleasant. The hot season commences in March and lasts till the middle of June by which time, the south-west monsoon starts. Thunderstorms are quite frequent during the hot season and some of them result in rains., the intensity of such rainfall being comparatively more in the hills than in the plains. The rains of this season are of great importance to agricultural operations in view of the soil preparation needed for the kharif crops. The south-west monsoon setting by the middle of June over the entire basin continues to be active in the first week of October. Durig this period the basin receives about 90 % of the annual rainfall. After withdrawl of south-monsoon also a few thunder storms continue to occur. The weather clears up by November and it is cold thereafter.

II.4.1 Rainfall : The basin average annual rainfall is 142cm. The rainfall during the period June to September is about 85 % of the annual rainfall, and about 90 % of the annual rainfall occurs during the period June to October.

II.4.2 Temperature : Generally, December is the coldest month with the minimum temperature ranging between 10<sup>o</sup> c and 13.7<sup>o</sup> c whereas, near the coast, it usually does not fall below 15.8<sup>o</sup> c. May is generally the hottest month of the year when the mean maximum temperature ranges from 38<sup>o</sup> c over the hills to 43<sup>o</sup> c in the plains.

## II.5 Mineral Resources

A part of the richest mineral belt of the sub-continent falls in the Mahanadi basin. The upper reaches of the basin consisting of the districts Bastar and Durg have huge quantities of iron ore deposits. Iron ore deposits are found in Sundargarh, Cuttack and Sambalpur districts also. Raigarh, Suruguja and Bilaspur districts have huge deposits of coal. Lime stone deposits are found in Durg, Raipur, Raigarh, Bilaspur, Sundargarh and Sambalpur. Dolomite occurrences are found in Sundargarh district. Deposits of Bauxite have been found in Suruguja, Bilaspur, Bastar and Raigarh districts of Madhya Pradesh. Bauxite is also found in Kalahandi and Sambalpur districts of Orissa. China clay is found in Durg, Bilaspur, Sambalpur and Sundargarh. Copper deposits are reported from Bastar district. Deposits of alluvial gold have been reported from Khairagarh Tehsil of Rajnandgaon district of Madhya Pradesh. In the coastal districts

of Cuttack and Puri, salt is available though not economically exploitable. Other minerals like Lead, Talc, Soap stone, Mica and graphite etc. are also reported from some parts of the basin.

## II.6 Industries

Rich in forest, agricultural and mineral resources, the industrial potential of the basin is much better than that of many other parts of India. Only a small part of the enormous forest wealth is at present being exploited for timber, paper and other industries. Among agricultural based industries, mention may be made of processing industries like rice-milling, manufacture of sugar and textiles, extraction of oil from groundnut, linseed and other oil seeds. Mining of coal, iron, manganese etc. is the other important activity in mineral rich districts.

Iron and steel are produced at Bhillai. Many other small engineering industries are spread all over the basin. Cement is manufactured in Raipur, Bilaspur and Sambalpur districts of the basin. Aluminium is produced at Korba and at Hirakud. A large Aluminium complex has come up in Koraput district of Orissa.

## METHODOLOGY

Water and sediment samples were collected from Mahanadi and its tributaries in December, 1986 (pre-monsoon) and August-September, 1987 (monsoon). The sampling locations are shown in Fig. III.1. The pre-monsoon samples are represented by the symbol (O) and the monsoon samples are represented by the symbol (X). The pH and alkalinity were measured immediately in field. The pH and EC were measured in the laboratory by CONSORT C425. The samples were filtered through millipore 0.45 micron membrane filters to collect the suspended matter and the filtered water was used for elemental analyses. Chlorinity was measured by  $\text{AgNO}_3$  titration, bicarbonate by potentiometric titration, sulphate by titration method after Fritz and Yamamura (1955) and Haartz et al. (1979). Fluoride by pH/Ionmeter 135. Phosphate and dissolved silica by ascorbic acid and molybdo-sillicate method respectively using UV spectrophotometer. The four major cations Ca, Mg, Na and K were analysed by the Atomic Absorption Spectrophotometer model GBC 902, Na, K by emission mode and Ca, Mg by absorption mode. Slides of suspended and bed sediments were prepared by drop-on slide technique (Gibbs, 1967a), glycolated and run on Phillips x-ray diffractometer using  $\text{CuK}_\alpha$  radiation and Ni filter. Size analyses for eight suspended sediments were done by Particle size Analyser model SA-CP2 (IIT, B). The grain size distribution of bed sediments were done by FRITSCH analysette type 03.502. Details of the analytical procedure is given in Appendix.

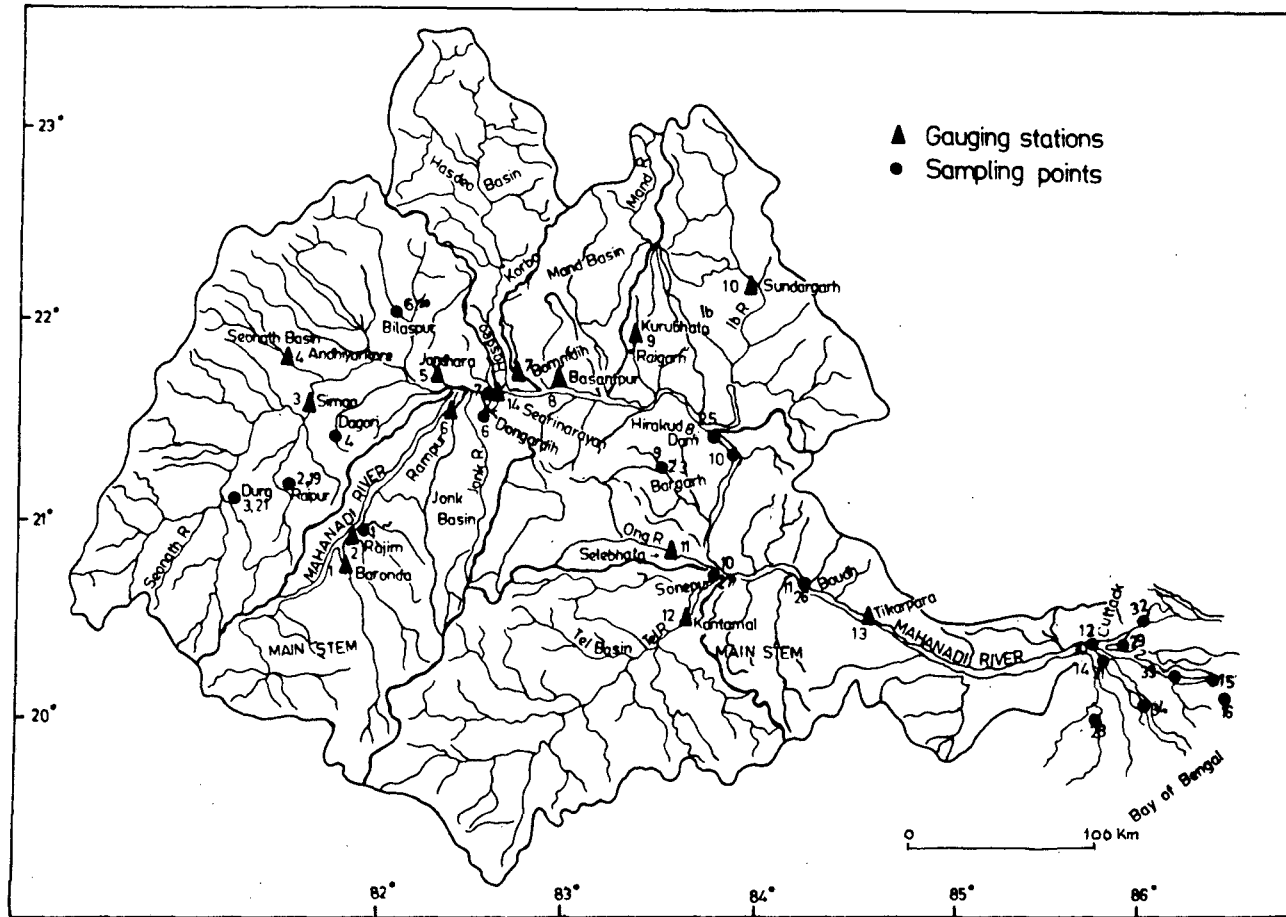


Figure III.1: Sampling locations (●) and CWC gauging stations (▲).

## RESULT AND DISCUSSION

IV.1 Major Ion Chemistry

The major cation and anion concentrations were determined in the Laboratory following various methods described in earlier chapter. The ionic balance indicates that the analytical methods followed gave results within a precision of 5-10 %. The results of the water analyses for both the seasons is given in Table IV.1 (A & B). A discussion on the chemistry of the river water is as follows :

pH and Electrical Conductivity (EC) : With an average pH of 7.67, the Mahanadi river water is alkaline in nature for both seasons (pre-monsoon and monsoon). The pH in pre-monsoon season is slightly more alkaline than the monsoon season. The alkalinity increases downstream. Subramanian (1979), reported for Indian rivers that, the alkalinity increases downstream independent of basin characteristics. The pH of most natural waters is of significance in all chemical reactions associated with the formation, alteration and dissolution of minerals (Stumm and Morgan, 1981 ). Subramanian (1979), observed that additional pH-buffering mechanisms operate in the Indian river systems, since the  $\text{HCO}_3^-$  concentrations are uniformly high and the observed pH is higher than the theoretical values based on alkalinity.

Table IV.I (A).

-1

Chemical analysis of Mahanadi river water (Dec. 86, units in mg L<sup>-1</sup>)

Sample No.	pH	EC (μS/cm)	F <sup>-</sup>	Cl <sup>-</sup>	HCO <sub>3</sub> <sup>-</sup>	PO <sub>4</sub> <sup>-</sup>	SO <sub>4</sub> <sup>-</sup>	SiO <sub>2</sub>	Na <sup>+</sup>	K <sup>+</sup>	Ca <sup>++</sup>	Mg <sup>++</sup>	TDS	TSM	Σ <sup>-</sup> (meq)	Σ <sup>+</sup> (meq)
1	8.26	338	0.023	22	190	-	2.5	19.0	25.70	9.16	24.23	16.7	309.31	16.07	3.78	3.72
2	8.10	131	0.014	11	84	-	1.0	14.7	10.86	8.57	14.12	8.1	152.36	3.02	1.70	1.22
3	8.16	304	0.023	33	195	-	2.0	12.4	15.62	7.37	42.67	15.9	323.98	64.76	4.18	4.29
4	7.80	180	0.015	24	140	-	1.0	14.8	11.26	7.12	35.06	5.8	239.05	12.95	2.99	2.50
5	8.33	350	0.039	26	220	-	3.0	17.4	24.30	9.64	32.06	15.5	347.93	29.12	4.41	3.86
6	6.82	208	0.015	34	128	-	1.5	15.3	16.74	10.65	20.51	12.1	238.48	203.51	3.09	3.04
7	6.92	230	0.020	12	163	0.003	2.0	15.1	15.62	8.35	28.09	14.3	258.58	17.2	3.08	3.47
8	8.38	132	0.015	24	82	0.004	2.5	12.8	10.91	6.18	17.58	7.9	163.89	5.0	2.06	2.14
9	7.37	180	0.017	22	130	0.005	2.5	16.4	19.31	6.20	21.93	13.4	231.76	13.80	2.78	3.18
10	8.48	163	0.019	11	115	0.004	5.0	13.1	13.61	8.31	23.03	22.4	211.47	9.46	2.32	3.81
11	8.57	149	0.019	22	112	0.004	1.0	15.1	11.60	6.58	18.57	9.2	196.07	15.33	2.47	2.34
12	8.40	162	0.018	24	128	0.004	4.0	15.1	13.71	7.32	17.65	14.5	225.80	10.00	2.87	2.85
13	8.32	226	0.017	22	130	0.004	2.0	16.6	17.81	9.49	21.80	13.5	235.51	4.10	2.77	3.22
14	7.68	340	0.017	34	182	0.018	1.5	18.9	19.51	16.38	32.68	16.0	314.50	4.10	3.98	4.22
15	8.13	29600	0.032	13400	135	0.004	194.0	0.7	12620.0	845.00	413.4	2315	29922	2223	-	-
16	8.07	30100	0.033	16530	130	0.004	212.0	0.8	14500.0	896.00	364.5	2345	34978	4271	-	-

Table IV.1 (B)

Chemical analysis of Mahanadi river water ( Aug-Sept.87, units in mg L<sup>-1</sup> )

Sample No.	pH	EC (μS/cm)	F	Cl	HCO <sub>3</sub>	PO <sub>4</sub>	SO <sub>4</sub>	SiO <sub>2</sub>	Na	K	Ca	Mg	TDS	TSM	Σ <sup>-</sup> (meq)	Σ <sup>+</sup> (meq)
17	7.26	83	0.011	34	64	-	1.5	16.6	10.07	8.02	10.72	7.1	152.02	69.60	2.04	1.75
18	7.94	290	0.042	26	250	0.01	10.0	17.5	31.26	10.25	33.68	14.5	393.24	46.00	5.09	4.49
19	7.48	188	0.012	21	120	0.009	2.5	30.1	15.30	8.94	23.18	9.0	230.04	23.20	2.62	2.68
20	7.36	135	0.013	42	122	0.008	2.5	20.7	10.25	8.84	32.06	1.9	240.02	211.20	3.26	2.09
21	7.30	111	0.012	21	70	0.005	3.5	12.2	10.07	13.07	12.58	5.1	147.53	859.6	1.74	1.84
22	7.14	126	0.012	20	105	0.007	1.5	16.4	10.56	7.19	20.83	8.7	190.19	328.8	2.32	2.39
23	7.64	195	0.015	14	145	0.012	3.0	11.9	11.84	6.68	29.58	8.2	230.22	34.4	2.10	2.83
24	7.32	105	0.020	17	62	0.012	8.0	17.1	8.28	6.50	12.7	6.2	137.38	440.0	1.71	1.64
25	6.92	69	0.017	55	60	0.005	1.0	18.9	7.79	8.34	14.98	9.7	175.73	166.8	2.57	2.13
26	7.29	140	0.016	28	145	0.012	3.0	17.7	14.24	5.57	21.56	10.5	245.59	82.4	3.24	2.70
27	7.88	170	0.022	10	120	-	4.0	21.7	12.27	8.67	17.49	8.8	202.95	562.8	2.34	2.35
28	7.45	217	0.047	25	125	0.006	3.0	17.9	13.77	13.47	23.45	11.1	233.10	33.2	2.82	3.02
29	7.38	132	0.017	18	82	0.012	2.0	19.0	11.71	6.31	15.46	8.1	162.60	51.2	1.90	2.10
30	7.43	198	0.010	14	140	0.011	1.0	13.8	13.41	12.26	20.32	13.0	227.81	198.4	2.69	2.98
31	7.09	91	0.013	18	85	0.007	4.5	13.6	11.43	8.57	13.94	6.5	161.56	219.2	2.01	1.93
32	7.56	146	0.020	14	145	0.011	3.5	18.7	10.12	7.09	30.06	3.8	232.30	210.8	2.87	2.13
33	7.41	135	0.011	52	90	0.010	2.5	21.3	10.90	4.69	15.90	12.1	209.41	20.8	2.71	2.38
34	7.30	112	0.010	13	95	0.080	2.5	13.3	13.59	5.79	16.67	8.1	168.04	33.2	1.98	2.23

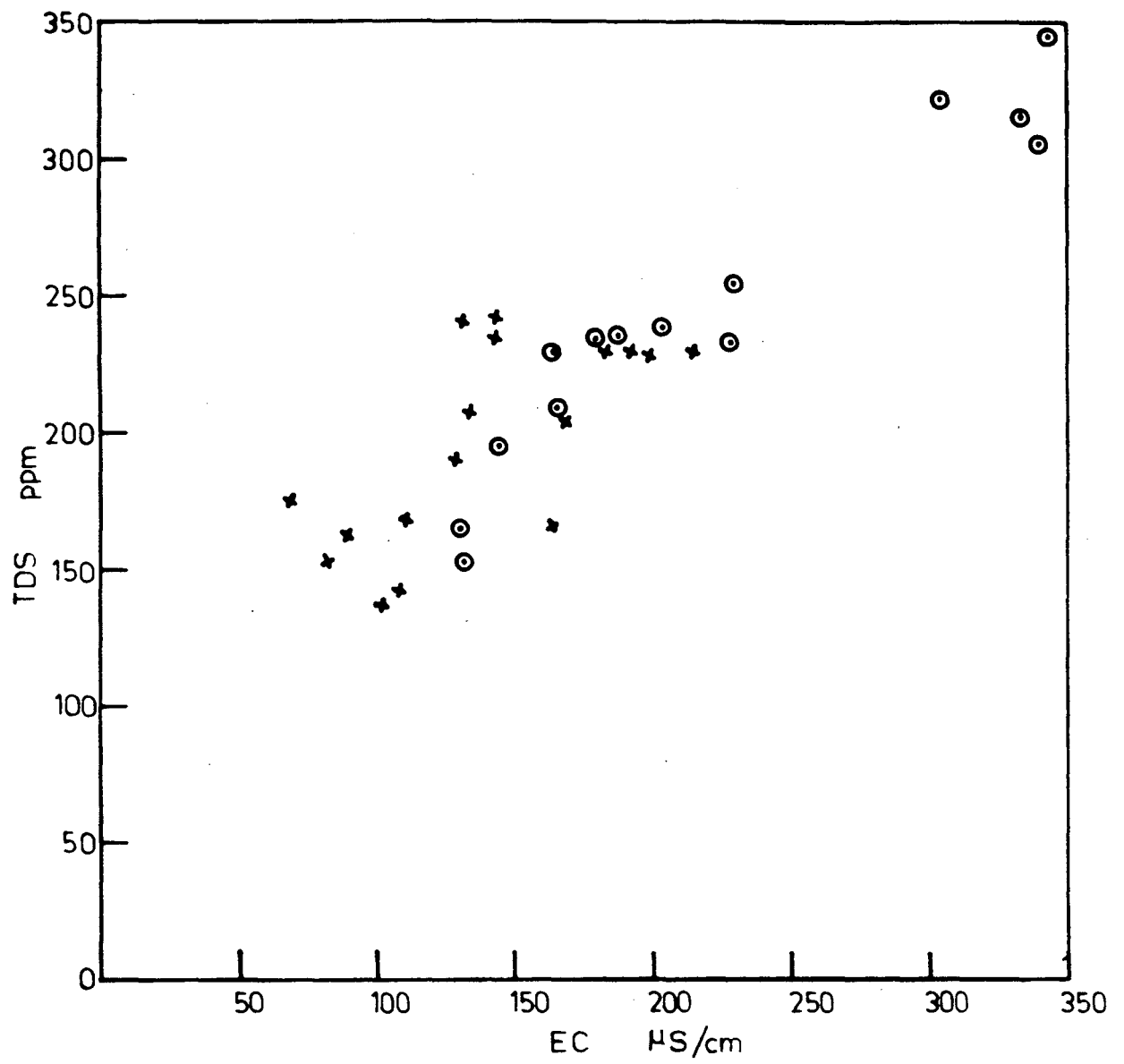


The EC shows seasonal variation. It is minimum in monsoon season and higher in pre-monsoon season. For example, the EC at Seorinarayan is 230  $\mu\text{S}/\text{cm}$ . in Dec.86 whereas in Aug.87 it reduces to 126  $\mu\text{S}/\text{cm}$ . an increase in EC reflects an increase in the ionic strength of the solution which in turn indicates an increased concentration of major ions. Correspondingly, the ionic strength ( $I = \frac{1}{2} \sum m_i z_i^2$ , where  $m_i$  is the molality and  $z_i$  is the charge of the  $i^{\text{th}}$  ion in the solution, the assumption being taken over all ions, positive and negative. Garrels and Christ, 1965) of Mahanadi varies from 0.003 in monsoon to 0.0045 in pre-monsoon season. Approximate TDS values can be computed from the measured EC by converting it with the commonly accepted factor of 0.7 for fresh water (Davies and Deweist, 1962). The correlation coefficient for EC and observed TDS shown in Fig. IV.1 gives a value of 0.895 for Mahanadi.

#### IV. 1.1 Major Anions

The major anions which make up more than 70 % of the total ions in the river water of Mahanadi are  $\text{Cl}^-$ ,  $\text{HCO}_3^-$  and  $\text{SO}_4^{--}$ .

The major source of chloride in river water is atmospheric precipitation. Barring areas of heavy industrial pollution, atmospheric chloride concentration by evaporation can not exceed 20 ppm, in rivers from areas with a run off in excess of 20 cm per year (Holland, 1979). A good deal of non-atmospheric chloride in the rivers is derived from sedimentary rocks, possibly by the addition of sub-surface connate brines. The average chloride concentration in Mahanadi is higher (23 ppm) than the average of



**Figure IV.1: Total dissolved solids versus Electrical conductivity.**

other Indian rivers : Ganges, 5.6 ppm ;Brahmaputra, 15.0 ppm ;Yamuna, 5.4 ppm ;Godavari, 17.0 ppm ;Cauvery, 18.0 ppm ;Subramanian (1987) .Marine contribution has been responsible for the comparatively higher value for the Krishna river (38.0 ppm;Ramesh,1985). Since Yamuna basin is land-locked, its low value is assumed to be from rainfall,ground water discharge and dust-storm (Jha,1986). The monsoon samples in Mahanadi show higher chloride concentration than the pre-monsoon.

Sulphate in rivers is derived from a variety of sources.Weathering of sulphide and sulphate minerals and the sulphate derived from the sea are the major sources of primary sulphate. Most of the anthropogenic sulphate is produced during fossil fuel burning. Garrels and Mackenzie (1975) indicate an anthropogenic contribution of 45 % for the total river sulphate. The average sulphate content in Mahanadi is 3.0 ppm , which is far below the Indian average of 13.0 ppm ( Subramanian, 1987). Seasonal and longitudinal variation of sulphate concentration of Mahanadi is not significant.

The possible sources of bicarbonate to the river water are atmospheric  $\text{CO}_2$ , dissolution of carbonate rocks, weathering of primary and secondary minerals and organic activities (Garrels and Mackenzie, 1971) and the high bicarbonate content all along the Mahanadi gives an indication of the intense chemical weathering taking place in it. Chemical weathering of pure calcite releases  $\text{Ca}^{++}$  and  $\text{HCO}_3^-$  in the molar ratio of 1:2 and dolomite releases  $\text{Ca}^{++}$ ,  $\text{Mg}^{++}$  and  $\text{HCO}_3^-$  in the ratio of 1:1:4

(Garrels and Mackenzie, 1971). Each molecule of  $\text{CO}_2$  produces one  $\text{HCO}_3^-$  ion from silicates and two  $\text{HCO}_3^-$  ions from carbonates. Generally, there is a decrease of bicarbonate content in monsoon season in Mahanadi. Ramesh (1985), reported for Krishna river that monsoon season shows a higher bicarbonate content compared to other seasons. This was, attributed to the fact that during monsoon period, atmospherically regulated  $\text{pCO}_2$ -water reactions may further enhance the bicarbonate alkalinity (Subramanian, 1983). A plot of  $\text{HCO}_3^-$ -Ca<sup>++</sup> for Mahanadi is shown in Fig.IV.2. Raymahasay (1986), has shown that the variation of bicarbonate in Indian rivers is primarily controlled by varying silicate fraction resulting from kaolinisation reactions. Based on Raymahasay's methodology (1986), Jha (1986) has calculated for Yamuna river that carbonate minerals contributes 57 - 90 % of bicarbonate and the rest comes from silicate minerals. Based on the  $\text{HCO}_3^-$  content and pH, the  $\text{pCO}_2$  of Mahanadi was calculated. The values lie between  $10^{-2}$  to  $10^{-3.5}$  atm. This is a global trend indicating that rivers are commonly out of equilibrium with the atmosphere.

#### IV. 1.2 Dissolved Silica ( $\text{SiO}_2^0$ )

Silica in river water is present largely as  $\text{H}_4\text{SiO}_4^0$ , derived from the weathering of silicate minerals. Dissolved silica at pH values less than 9 is present as monomeric sillicic acid,  $\text{H}_4\text{SiO}_4^0$  (Siever, 1971). At pH values above 9,  $\text{H}_4\text{SiO}_4^0$  dissociates to  $\text{H}_3\text{SiO}_4^-$  and  $\text{H}_2\text{SiO}_4^{--}$ . Dissolved silica concentrations appear to be higher in the monsoon for Mahanadi.

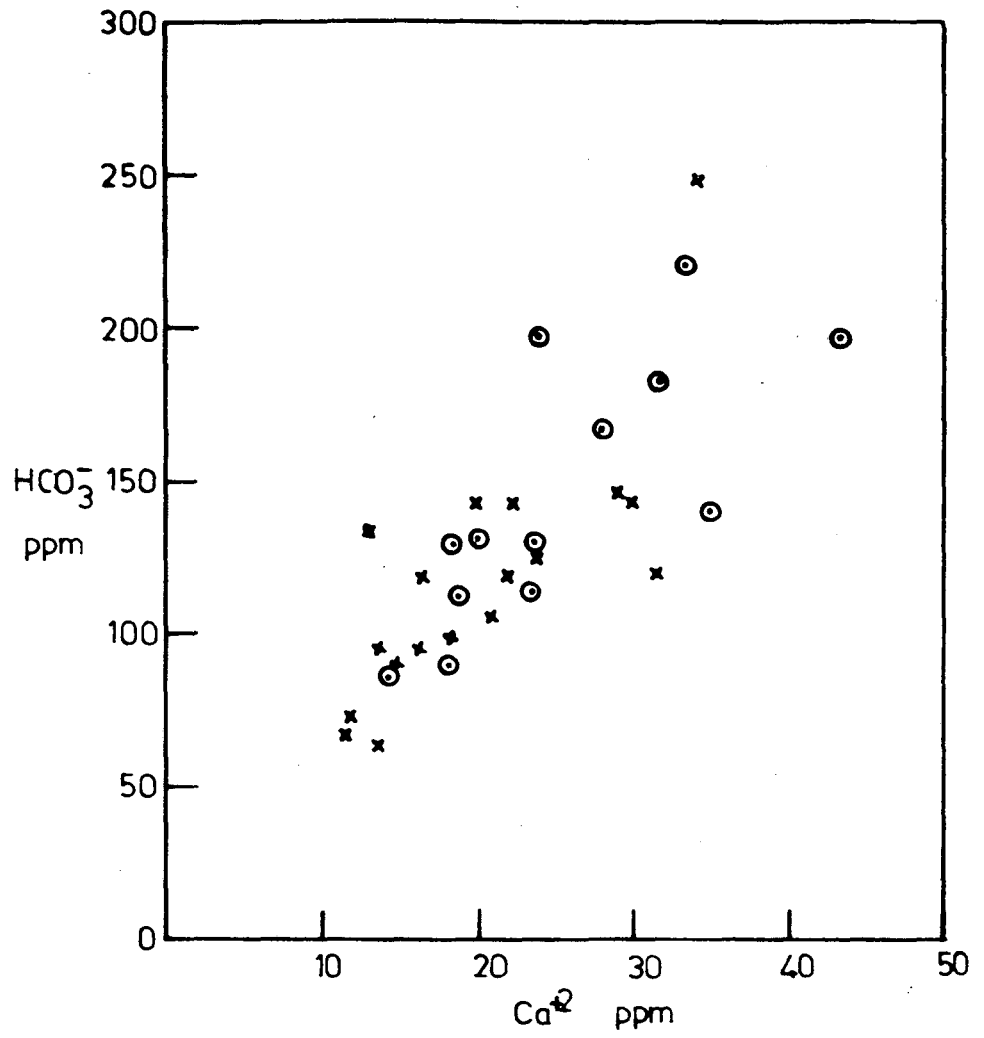


Figure IV.2: Calcium versus bicarbonate.

But Ramesh (1985), Jha (1986) reported respectively for Krishna and Yamuna river, higher values of silica during winter and pre-monsoon season. Mahanadi shows dissolved silica concentration of 17 ppm, which is higher than the Indian average (7 ppm, Subramanian, 1987) and world average (10.4 ppm, Meybeck, 1979). The possible source of the dissolved silica seems to be the kaolinisation of silicates such as feldspars, augite, biotite etc.

#### IV.1.3 Major Cations

The four major cations which were studied for Mahanadi are Ca, Mg, Na, and K which make up more than 25 % of the total ionic concentration.

Calcium in river water is derived largely from the weathering of carbonates, sulphates and silicates. Calcite, aragonite and dolomite are the important carbonates and gypsum, anhydrite, the important sulphates. The Pearson's correlation coefficient for Ca-Mg (0.99) in Fig.IV.3 shows that the source for Ca and Mg could be the same. The relationship for Ca<sup>++</sup> and

HCO<sub>3</sub><sup>-</sup> was discussed earlier.

Na<sup>+</sup> and K<sup>+</sup> make up 8 -10 % of the TDS in Mahanadi. Millot (1970) from his studies on hydrosphere came to the conclusion that in the course of continental weathering Na<sup>+</sup> turns out to be much more mobile than K<sup>+</sup> and dominates the latter in natural solutions. The present work indicates that most of Na<sup>+</sup> and Ca<sup>++</sup>

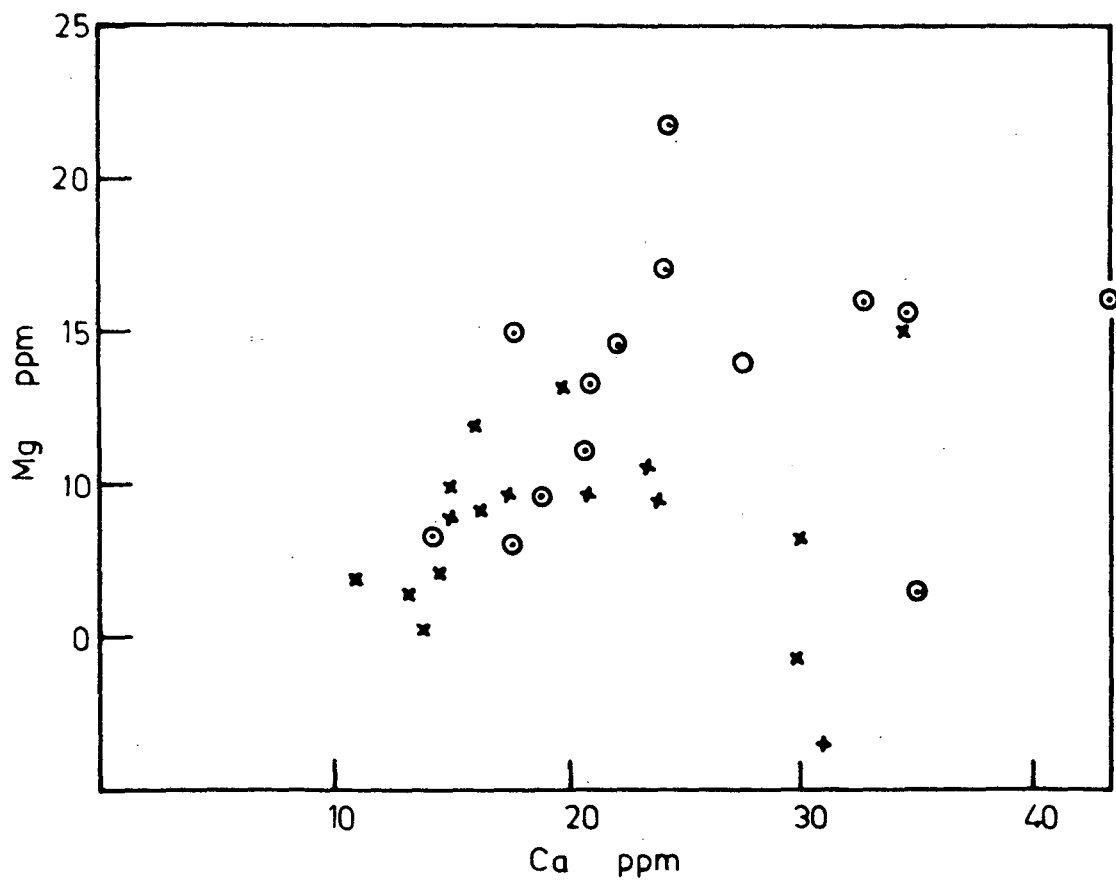


Figure IV.3: Calcium versus magnesium.

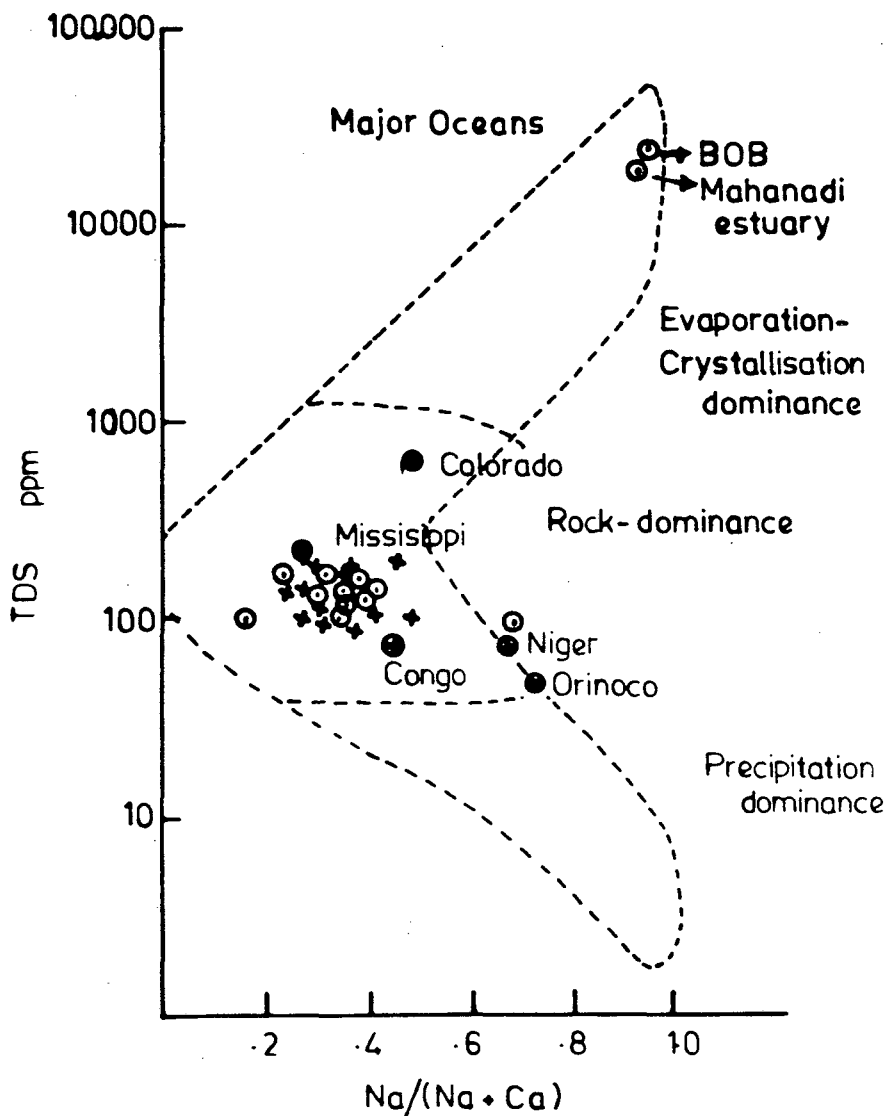


Figure IV.4: Variation of the weight ratio,  $\text{Na}/(\text{Na} + \text{Ca})$  as a function of total dissolved solids (Redrawn after R.J. Gibbs, 1970).



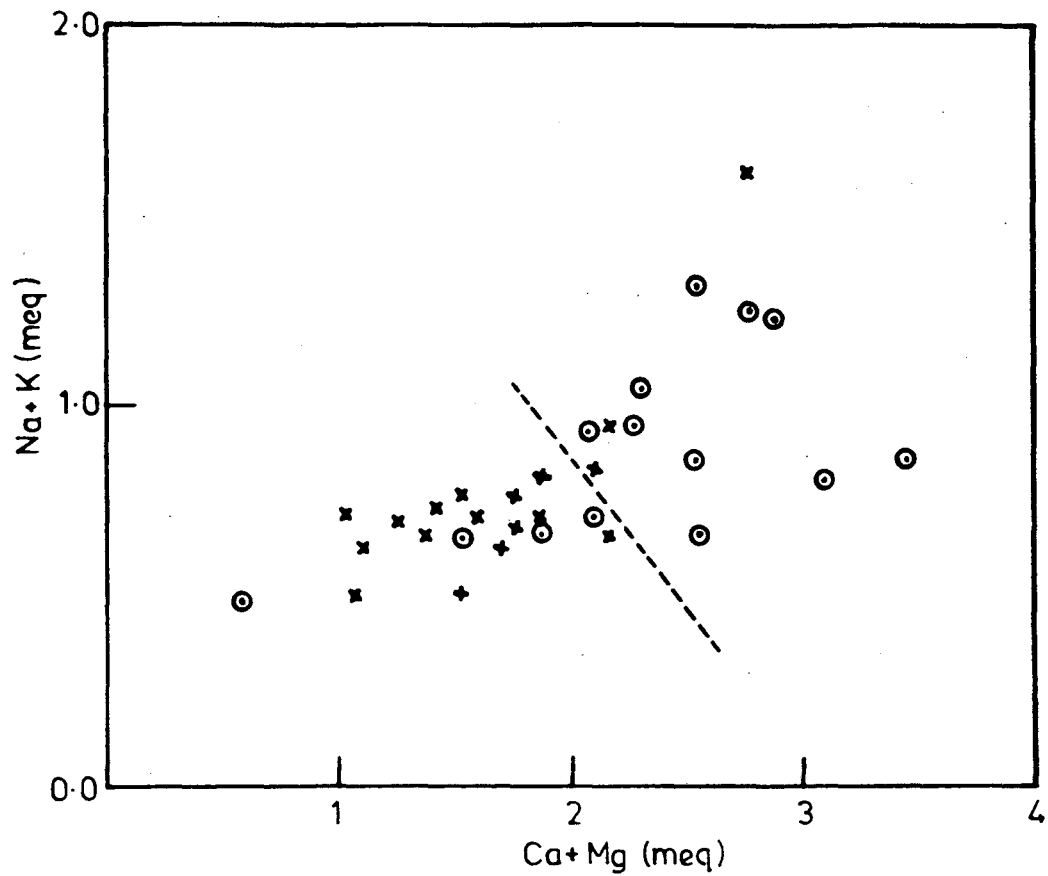


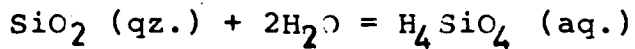
Figure IV.5: Ca + Mg versus Na + K. The line separates monsoon samples from the pre-monsoon.

are derived from continental weathering than atmospheric precipitation ( Fig. IV.4 ). The  $K^+$  comes from the kaolinisation of feldspar and dark silicate minerals like biotite, hornblende etc. Only 15 % of the river transport of  $K^+$  is in dissolved load while the rest is in particulate (Berner and Berner, 1987). The low  $K^+$  content compared to  $Na^+$  may be due to its uptake by clay minerals.

A plot of  $Ca + Mg - Na + K$  (Fig. IV.5) shows a clustering of points at two sides . The total cation concentration in monsoon is lower than the pre- monsoon. The  $Ca + Mg / Na + K$  ratio of Mahanadi (5.86) is more than twice the world average (2.2) and Indian average (2.5), implying that the carbonate source rock influences the water chemistry in Mahanadi. Sarin and Krishnaswamy (1984) observed that in the Ganges-Brahmaputra river system, the weathering of carbonates and contributions from soil salts and/or saline groundwater dictate the water chemistry. Subramanian and Abbas (1985) reported higher values of Ca, Mg, Ba and Sr in the Ganga sediments than the world average, due to contribution from the carbonate rocks of the basin.

#### IV.2 Water-Mineral Equilibria

The mineral stability can be predicted by the application of thermodynamic concepts to chemical equilibria of the water (Kramer, 1967). The simplest example of mineral solution equilibrium would be dissolution of a mineral such as quartz. At pH values below 9, this can be represented by the equation,



$$\begin{aligned} \text{Req.} &= a_{\text{H}_4\text{SiO}_4} \text{ (assuming } a_{\text{H}_2\text{O}} = 1) \\ &= 1 \times 10^{-4} \text{ at } 25^\circ \text{ c.} \end{aligned}$$

Any solution (at 25<sup>o</sup> c) in which  $a_{\text{H}_4\text{SiO}_4} = 1 \times 10^{-4}$  would be in equilibrium with quartz. Solutions with higher  $a_{\text{H}_4\text{SiO}_4}$  values would be supersaturated and those with lower values would be undersaturated. Similar relationship holds for amorphous silica which has a solubility of  $2 \times 10^{-3}$  at 25<sup>o</sup> c.

Water derives its composition from the parent rock in the weathering region, the suspended sediments owe their mineralogical composition partly to the parent rock and partly to the chemical reaction of rock and water. When such reactions reach chemical equilibrium, certain mineral assemblages would co-exist in the sediment phase provided the chemistry of the water remains same. Thus, by studying the water chemistry, stable mineral assemblages can be predicted. All reactions were assumed to take place at constant temperature (25<sup>o</sup> c) and pressure (1 atm.) . Berner (1971); Garrels and Christ (1967); Garrels and Mackenzie (1971); Jacks (1973); Jha (1986); Ramesh (1983,85); Ramesh and Subramanian (1984,87); Subramanian (1979); Subramanian and d'Anglejan (1970) and several others have predicted the presence of theoretical mineral assemblages using different natural water bodies, expected in equilibrating sediments. An attempt has been made in this study to apply similar concepts to the Mahanadi river water. From the chemical composition of

Mahanadi river water, molality, ionic strength, activity coefficients, activity and negative logs of ion activities for sillicate and carbonate systems have been calculated.

#### IV. 2.1 Carbonate system

Carpenter (1962), has developed a diagram that shows metastable and stable equilibria among the calcium and magnesium carbonates (Fig.IV.6). The metastable phases involved are aragonite and huntite. The early mineral compatibilities are those that would be deduced from the metastable (dashed lines) diagram, these early minerals apparently eventually equilibriate to give the phase relations demonstrated by the solid lines. The phase diagram shows dolomite to be a stable assemblage irrespective of the season. Subramanian (1979), reported that dolomite is the theoretically expected mineral in the river waters of India. The x-ray diffraction studies of the suspended sediments discussed in the later section shows considerable amount of dolomite as well as calcite in all samples. Dolomite formation does not result from the combination of  $\text{Ca}^{++}$ ,  $\text{Mg}^{++}$  and  $\text{CO}_3^{--}$  ions, but result from the combination of  $\text{CaCO}_3$  (calcite) with  $\text{Mg}^{++}$ .

#### IV.2.2 Sillicate System

The chemistry of river water can be represented in a phase diagram consisting of  $\text{K}_2\text{O}-\text{Na}_2\text{O}-\text{MgO}-\text{CaO}-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{H}_2\text{O}$  components. The composition of Mahanadi river water has been plotted in mineral stability diagram in Fig .IV.7 (A,B,C,D,E).The

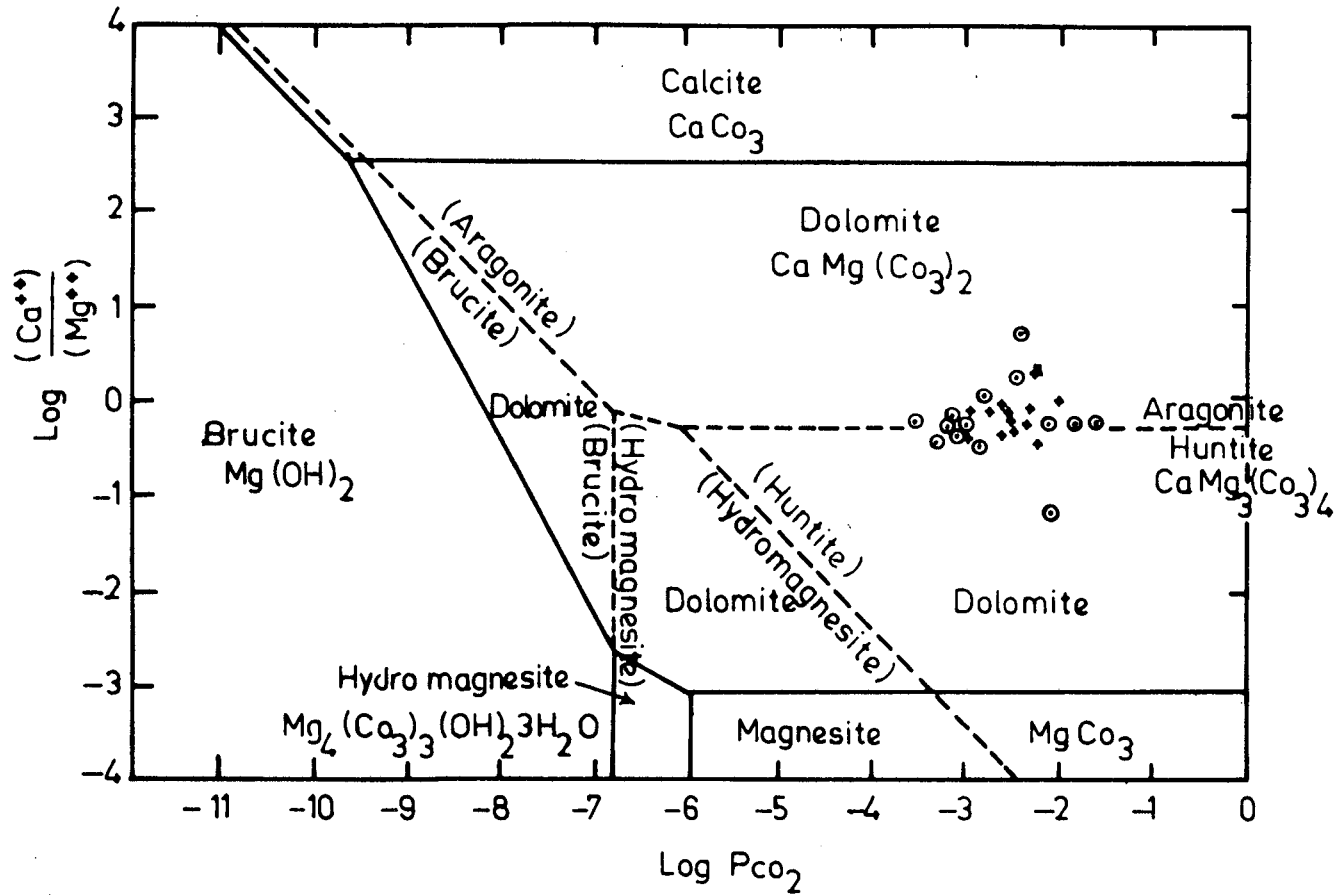


Figure IV.6: Equilibrium diagram in carbonate system. Dolomite seems to be a stable mineral in Mahanadi.

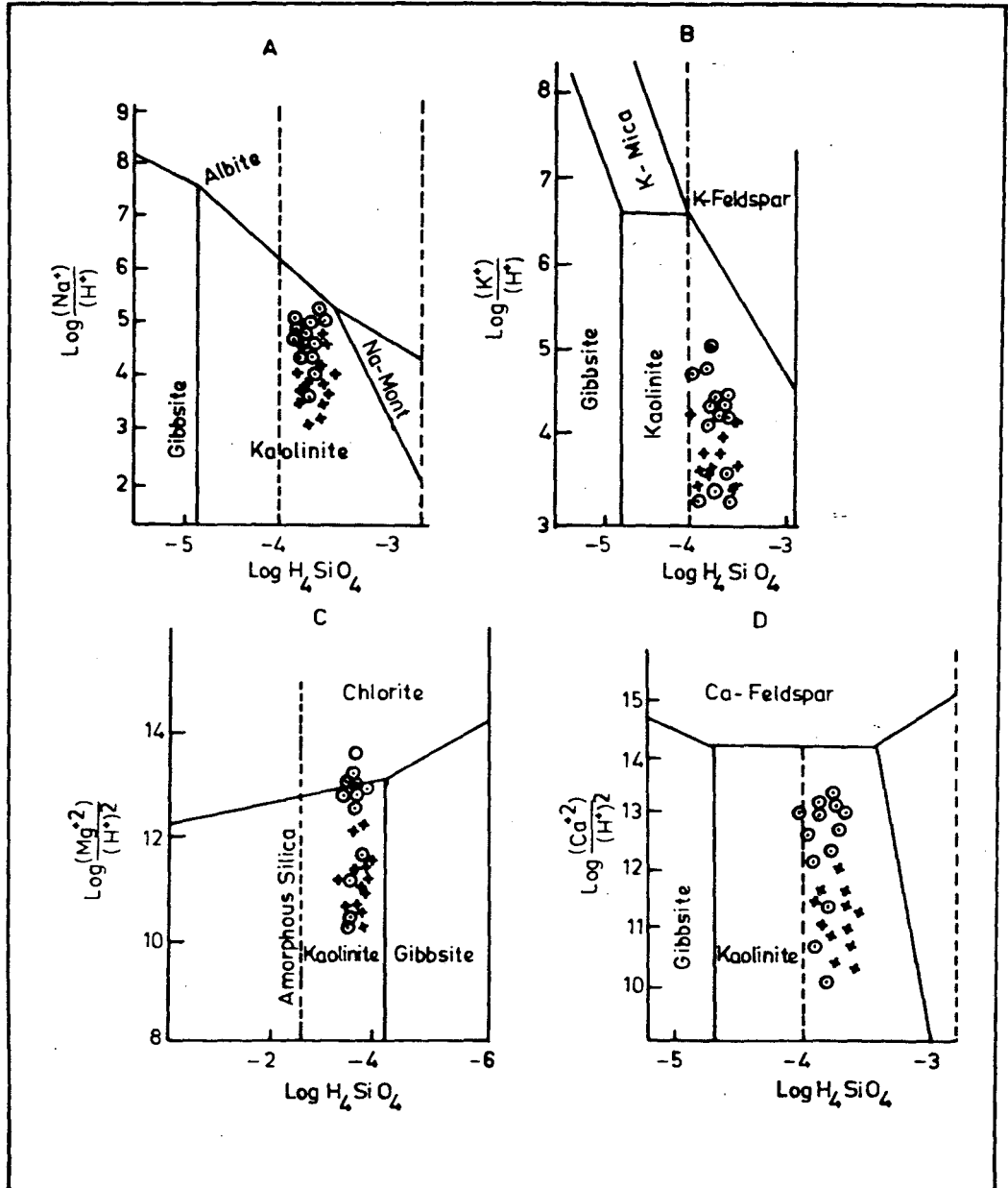


Figure IV.7: (A,B,C,D) Equilibrium diagrams for silicate system. Kaolinite, Chlorite are stable silicates in Mahanadi.

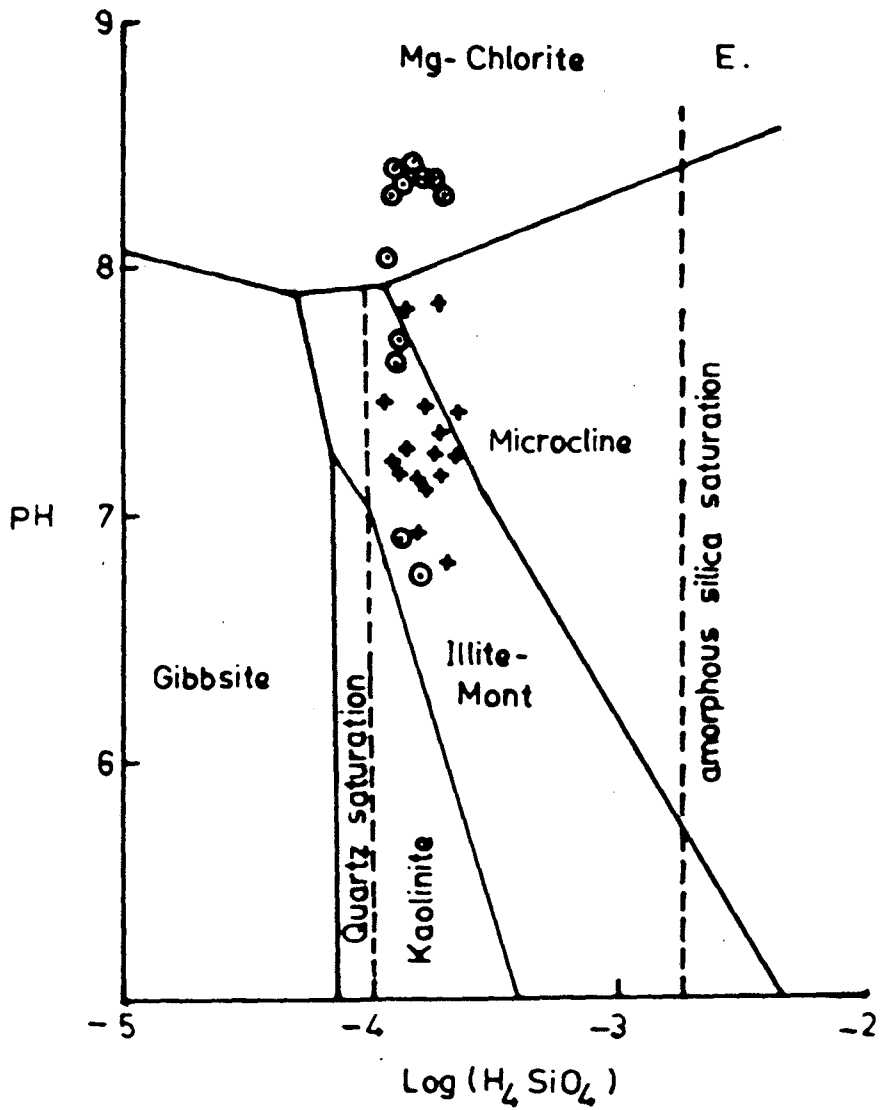


Figure IV.7: (E) Chlorite and Illite-montmorillonite are stable silicates in Mahanadi.

majority of data points fall in the kolinite region, except for Mg-alluminosilicate system where chlorite seemsto be the stable mineral phase. Some samples also indicate the presence of illite-montmorillonite. Garrels and Mackenzie (1971), have shown that the plot of river water generally falls in k-mica region for k-alluminosilicate system. Subramanian (1979), reported that independent of cation considered, kaolinite is the theoretically expected mineral in river waters of India. X-ray mineralogical studies of the Mahanadi river suspended sediments show the presence of the above predicted minerals.

#### IV.3 Erosion rate in the Mahanadi river

The water and sediment discharge data was obtained from the Central Water Commission for the years 1980-81, 1981-82, 1982-83, 1983-84 . Table IV.2 gives the average annual water and sediment discharge for the four years. More than 95 % of the discharge is in the months of Aug.-Sept. which represent the monsoon season. Fig.IV.8 compares the water and sediment discharge for six locations for the four years. Since the samples for the present study were not collected from the same place, where the CWC stations are located, the nearby station's discharge data were used for calculation of erosion rate, elemental fluxes etc. Table IV.3 gives the hydrological and erosional characteristics of Mahanadi and the same for the CWC gauging stations in Mahanadi is given in Table IV.4.



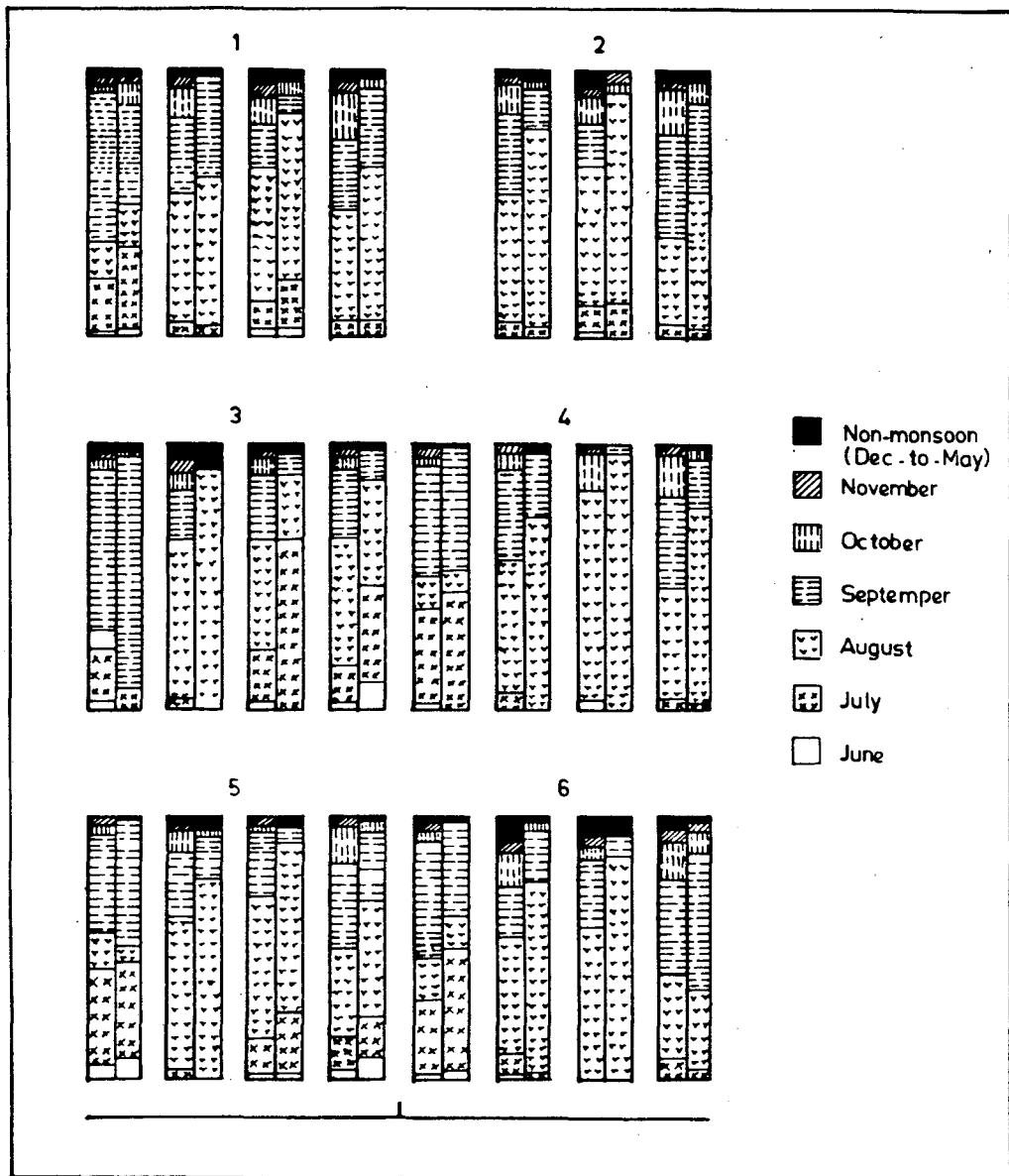


Figure IV.8: A comparison of water and sediment discharge for six CWC gauging stations along Mahanadi. Left side of the bar gives the water discharge and right side, sediment discharge in percentage. 1. Simga 2. Jondhra 3. Rajim 4. Rampur 5. Kantamal 6. Tikarpara.

Table IV.2

Water and sediment discharge for the CWC gauging stations

Basin	Water discharge ( m <sup>3</sup> /sec )				Sediment discharge ( 10 <sup>6</sup> t )			
	1980-81	1981-82	1982-83	1983-84	1980-81	1981-82	1982-83	1983-84
Basantpur	1036	592	457	658	36.17	15.23	8.53	16.32
Rampur	92	27	39	30	1.06	0.4	0.9	0.34
Bamnidihi	262	141	142	147	7.08	2.73	4.96	4.98
Rajim	148	61	47	57	13.59	1.89	0.79	0.59
Simga	245	148	111	170	3.41	1.70	1.34	2.04
Salebhata	92	51	79	57	2.03	0.63	4.02	0.85
Tikarpara	2164	1183	1349	1714	43.78	19.10	42.12	22.22
Kantamal	428	220	182	208	9.71	6.38	5.87	5.19
Andhiyarkore	13	8	5	15	0.9	0.39	0.45	0.49
Baronda	67	22	24	-	8.03	0.23	0.83	-
Jondhra	27	223	160	315	0.01	2.54	3.74	5.24
Kurubhata	70	56	64	77	2.47	1.58	2.60	2.55
Sundargarh	101	99	71	98	2.20	3.08	2.63	2.45

Table IV.3

Hydrological and Erosional characteristics of Mahanadi river

Location	Stream	Basin area (km <sup>2</sup> )	Elevation (m)	Water dis. (m <sup>3</sup> /sec)	Load (million tonnes/yr)			Erosion rate (t/km <sup>2</sup> /yr)		
					chemical	sediment	total	chemical	sediment	total
Raipur	Kharun	16060	936	168	1.23	0.35	1.58	76.7	22.9	99.6
Bilaspur	Arpa	29645	901	193	1.46	1.28	2.74	49.3	43.3	92.6
Rajim	Mahanadi	8760	1457	52	0.24	0.11	0.35	28.3	12.7	41.0
Seorinarayan	Mahanadi	9730	848	396	2.38	3.27	5.65	245.0	336.0	581.0
Sonepur	Mahanadi	19600	1361	258	1.65	4.48	6.13	84.3	229.0	313.0
Boudh	Mahanadi	41000	2208	1356	12.47	3.27	15.74	304.0	79.0	383.0

Table IV.4

Hydrological and Erosional characteristics of the CWC gauging stations of Mahanadi

Location	Stream	Basin area (km <sup>2</sup> )	Water dis. (m <sup>3</sup> /sec)	Sediment load (million tonnes)	Erosion rate (t/km <sup>2</sup> /yr)	Lowering of Land (cm/1000 yr)
Basantpur	Mahanadi	57780	686	19.07	330	12.5
Rampur	Jonk	2920	47	0.68	233	8.86
Bamnidi	Hasdeo	9730	173	15.93	498	18.9
Rajim	Mahanadi	8760	78	4.20	480	18.2
Simga	Seonath	16060	168	2.12	132	5.0
Salebhata	Ong	4650	70	1.90	405	15.4
Tikarapara	Mahanadi	41000	1603	31.81	776	29.4
Kantamal	Tel	19600	260	6.79	347	13.1
Andhiyarkore	Hamp	2210	10	0.56	255	9.7
Baronda	Pairi	3225	38	3.03	942	35.7
Jondhra	Seonath	29645	181	2.89	130	4.9
Kurubhata	Mand	4625	66	2.30	497	18.8
Sundargarh	Ib	5870	92	8.54	442	16.8

#### IV.3.1 Chemical and Physical Erosion Rate

The discharge weighted mean composition of Mahanadi and the individual elemental fluxes are given in Table IV.5 . The previously calculated erosion rate in Mahanadi is compared with other major world rivers in Table IV.6.

Dissolved transport dominates over Physical transport in Mahanadi by a factor of four. The global average of sediment to chemical load is 4.3 (Milliman and Meade, 1983). The natural factors which control the suspended sediment transport in rivers according to Milliman (1980) are, i) relief of the drainage basin ii) drainage basin area iii) discharge iv) geology of the river basin v) climate vi) presence of lakes along the river length. All the Indian rivers together contribute about 6 % of the chemical load which is high compared to its size (Subramanian, 1978). There is no relationship between sediment and chemical erosion rate for Mahanadi. Judson (1964), derived a negative logarithmic relationship between the chemical and sediment erosion rate. However, analyses of Indian rivers do not support Judson's proposition (Subramanian, 1978). For Mahanadi, there is a poor relationship between basin area and physical erosion rate ( $cc = 0.29$ ), elevation and physical erosion rate ( $cc = 0.28$ ). Eventhough, the chemical load of Amazon is nearly thrice that of Brahmaputra and many times that that of other Indian rivers, the erosion rates for any of the Indian rivers is much higher. So the size of the basin and the river discharge has no effect on the rate of chemical mass transfer (Subramanian, 1978). Mahanadi, like

Table IV.5

Discharge weighted mean composition of Mahanadi river at six locations

Location	Stream	F	Cl	HCO <sub>3</sub>	PO <sub>4</sub>	SO <sub>4</sub>	SiO <sub>2</sub>	Na	K	Ca	Mg
Raipur	Kharun	a.0.012	21.03	122.53	0.008	2.5	29.71	15.68	8.94	23.21	9.27
		b.0.063	111.30	648.53	0.042	13.23	157.25	82.99	47.31	122.8	49.06
		c.0.005	9.03	52.61	0.003	1.07	12.75	6.73	3.83	9.96	3.98
Bilaspur	Arpa	a.0.013	41.68	122.23	0.007	2.4	20.63	20.89	8.91	31.59	2.48
		b.0.079	253.96	744.78	0.042	14.98	125.7	127.28	54.29	192.48	15.11
		c.0.005	16.61	48.71	0.002	0.98	8.22	8.32	3.55	12.59	0.98
Rajim	Mahanadi	a.0.011	33.63	64.29	-	1.5	16.57	10.08	8.02	10.76	7.11
		b.0.017	55.01	105.17	-	2.43	27.1	16.49	13.12	17.60	11.63
		c.0.007	22.13	42.33	-	0.98	10.9	6.63	5.27	7.08	4.67
Seori- narayan	Mahanadi	a.0.011	19.83	106.19	0.006	1.5	16.37	10.66	7.21	20.97	8.76
		b.0.013	247.47	1325.12	0.074	18.84	204.29	133.03	89.98	261	109.3
		c.0.005	10.35	55.4	0.003	0.78	8.54	5.56	3.76	10.94	4.57
Sonepur	Mahanadi	a.0.022	10.02	119.89	-	4.02	21.52	12.29	8.66	17.59	9.08
		b.0.179	81.57	976.02	-	32.72	175.19	100.05	70.50	143.20	73.92
		c.0.010	4.93	59.03	-	1.97	10.59	6.05	4.26	8.66	4.47
Boudh	Mahanadi	a.0.016	27.52	142.39	0.011	2.90	17.5	14.03	5.64	21.32	10.39
		b.0.068	117.64	608.71	0.047	12.14	74.76	59.97	24.11	9.14	44.41
		c.0.006	11.38	58.92	0.004	1.17	7.23	5.80	2.33	8.82	4.29

a. discharge weighted average concentration.(ppm)  
b. flux in  $10^3$  tonnes/km<sup>2</sup>/yr.  
c. percentage of total flux.

Table IV.6

Erosion rates of some important rivers in the world

River	Discharge ( $10^3 \text{ m}^3/\text{yr}$ )	Drainage area ( $10^3 \text{ km}^2$ )	Load (million tonnes/yr)			Erosion rate (tonnes/ $\text{km}^2/\text{yr}$ )			sed./chem.
			chem.	sed.	total	chem.	sed.	total	
Krishna	30	251	10.4	4	14.4	41	16	57	0.39
Godavari	92	310	17.0	170	187.0	55	555	610	10.0
Cauvery	21	88	3.5	0.04	3.54	40	0.5	40.5	0.01
Brahmaputra	510	580	51.0	597.0	648.0	88	865.0	953.0	9.80
Ganges	493	750	84.0	329.0	413.0	111	438.0	549.0	3.90
Huang- He	48	745	22.0	1080.0	1102.0	30	1402.0	1432.0	46.7
Yangtze	1063	1950	226.0	478.0	704.0	116	246.0	362.0	2.1
Amazon	5500	6300	287.0	900.0	1187.0	46	146.0	192.0	3.1
Irrawady	422	430	90.0	285.0	375.0	211	662.0	873.0	3.1
Magdalena	236	240	28.0	220.0	248.0	117	916.0	1033.0	7.8
Mississippi	580	3267	131.0	210.0	341.0	40	64.0	104.0	1.6
Orinoco	946	950	50.0	210.0	260.0	52	212.0	264.0	4.0
Mekong	666	795	59.0	160.0	219.0	74.0	200.0	274.0	2.7
Mahanadi*	67	142	9.6	1.9	11.5	67.6	13.3	80.9	0.19
World - average	31400	101000	3600.0	13505.0	17105.0	35.0	150.0	185.0	4.3

Compiled from Ph.D. thesis (Ramesh,1985).

\* present work.

other non-Himalayan rivers is chemically more active. The total erosion rate is dependent on the basin area ( $cc = 0.73$ ) and elevation ( $cc = 0.77$ ) for Mahanadi.

The sediment transport by Mahanadi is quite insignificant compared to the Himalayan rivers. Ganges and Brahmaputra together account for nearly 90 % of the total sediment transfer from the Indian sub-continent. The basin area of the Himalayan system (60 % area lies in the mountains) is less than half that of Amazon (12 % area lies in mountains), but their sediment contribution is nearly same as that of the Amazon. This speaks of the control of relief in dictating the environment in drainage basin. Mahanadi at Tirtol delivers 11.56 million tonnes of load (9.66 million tonnes dissolved load and 1.9 million tonnes sediment load) annually to the Bay of Bengal. This represents about 3.5 % and 4.5 % of total chemical and sediment load respectively transported by Indian rivers. The rate of lowering of the drainage basin of Mahanadi on the average is 1.59 mm/yr. Judson (1964), estimated an average erosion rate of 0.158 mm/yr for the Colorado basin and 0.038 mm/yr for the Columbia river basin. Subramanian (1978), calculated that the river basin reduces at a rate of 45.1 mm/yr for Brahmaputra, 2.2 mm/yr for Godavari and 5.9 mm/yr for Krishna. Based on these data, he estimated that the entire Indian sub-continent would have been levelled to the sea in five million years from now.



#### IV.4 Physical and Chemical Characteristics of Suspended and Bed Sediments

##### IV.4.1 Grain-size Distribution

Grain-size study is a fundamental descriptive measure of sediments and sedimentary rocks. It is important in understanding the mechanisms operative during transportation and deposition, as well as the distance of transport. Several approaches have been used to interpret depositional environment from grain size distribution, such as plotting skewness versus sorting (Friedman, 1961), comparing coarsest fraction to the median size (Passega, 1964), and analysing cumulative curve shape (Visher, 1969). Middleton (1976) and Sagoe and Visher (1977), examined the relationship between grain-size distribution and hydraulics. In the present study, the characteristics of the grain-size distribution of the suspended and bed sediments of Mahanadi river have been studied and the various statistical parameters were determined by the method of moments. The formulas and verbal scales are after Folk and Ward (1957). Table IV.7 and IV.8 give the size distribution of suspended and bed sediments in percentage and in Table IV.9 and IV.10, the statistical parameters for the bed and suspended sediments are given.

##### IV.4.1.1 Mean size ( $M_z$ )

The suspended sediment consists of fine clay size particles (0.49 to 3.9 microns). The monsoon season samples have more finer suspended sediment than the pre-monsoon. For the bed sediments average mean size for bed sediments is 500 microns (i.e. medium

Table IV.7

Grain size distribution of bed sediments (in percent).

Size in $\mu$	2	3	4	6	7	8	9	10	11	12	13	14	15	16
1000	31.25	37.36	16.20	30.16	50.43	40.44	19.95	29.70	60.95	-	3.66	33.02	-	-
850	9.18	3.11	5.13	4.40	8.28	14.75	11.89	11.42	11.09	-	2.57	2.00	-	-
600	12.67	4.01	8.95	6.65	9.39	17.46	17.71	15.34	10.25	-	5.03	2.33	-	-
425	26.25	16.81	33.73	24.26	18.08	0.02	37.32	34.59	10.04	-	34.80	11.86	-	-
355	1.05	2.18	3.08	2.69	0.36	22.27	1.76	-	0.17	-	2.87	0.69	-	-
300	6.65	11.24	13.46	15.86	4.85	2.21	6.33	7.70	0.76	-	24.13	10.55	-	-
250	0.43	1.60	0.34	0.37	0.62	0.03	0.42	0.23	0.08	9.34	3.64	0.35	3.96	6.90
180	11.50	13.58	13.28	13.30	4.69	1.52	3.34	0.08	2.25	43.52	19.27	18.62	43.34	56.47
125	0.69	5.61	4.10	2.06	2.46	0.60	0.79	0.06	1.61	34.84	2.72	15.39	47.79	31.15
90	-	3.20	0.28	-	0.15	0.03	0.02	0.01	0.09	2.46	0.07	1.03	2.13	1.37
63	-	0.92	1.00	0.13	0.38	0.25	0.17	0.01	0.34	7.16	0.39	2.66	2.50	3.58
37	0.002	0.26	0.24	0.05	0.09	0.13	0.09	0.02	0.12	2.24	0.24	0.73	0.26	0.50
<37	0.01	0.15	0.14	0.02	0.16	0.22	0.16	0.01	2.20	0.42	0.53	0.24	-	-

Table IV.8

Grain size distribution of suspended sediments (in percent)

Size( $\mu$ )	3	6	16	22	25	26	31	34
20.0	1.8	30.8	50.5	-	-	9.1	-	-
10.0	7.9	11.5	39.5	-	-	7.7	-	-
8.0	15.6	1.2	5.8	-	-	2.6	-	-
6.0	19.9	15.0	4.2	-	-	1.1	-	-
5.0	7.0	0.4	-	-	-	-	-	7.1
4.0	1.8	4.2	-	-	-	-	-	1.0
3.0	1.0	0.4	-	-	-	-	-	0.3
2.0	-	-	-	-	-	-	-	8.1
1.0	5.5	4.4	-	3.8	3.3	9.1	4.9	19.5
0.8	4.0	2.3	-	1.7	7.2	5.0	3.5	6.8
0.6	3.3	1.1	-	4.9	9.5	8.8	7.8	5.0
0.5	3.5	2.6	-	5.5	6.9	6.6	6.1	2.7
0.4	5.9	3.3	-	9.6	11.6	11.4	9.1	2.8
0.3	7.1	6.7	-	14.5	16.0	11.9	18.0	3.3
0.2	9.0	8.2	-	21.3	18.5	12.7	21.7	5.2
<0.2	6.7	7.9	-	39.2	27.5	14.0	28.9	37.6

sand). The decrease of grain-size from Sambalpur to Jagatsinghpur reflects the influence of dams where most of the coarser particles are trapped.

#### IV.4.1.2 Standard Deviation ( $\sigma_i$ )

Standard deviation measures the sorting or uniformity of the particle size distribution. This reflects the consistency in the energy level of the depositing medium. The suspended sediments are moderately well sorted ( $\phi = 0.9$  to  $2.7$ ). The bed sediments are poor to moderately sorted ( $\phi = 0.36$  to  $1.25$ ). So the suspended sediments are more uniform in size distribution than the bed sediments.

#### IV.4.1.3 Skewness ( $SK_i$ )

Skewness measures the asymmetry of the distribution. If there is more material in the coarse tail (coarse skewed), the skewness is referred to as being negative. If there is more material in the fine tail (fine skewed), it is positive. Skewness is useful in identifying sedimentary environments where primary sedimentary structures are lacking. A number of authors (e.g. Awasthi, 1970; Cronan, 1972; Folk and Ward, 1957; Friedman, 1967; Martin, 1965; Sahu, 1964; Valia and Cameroon, 1977) have emphasised the importance of skewness as an indicator of Paleoenvironment. The average skewness of the suspended sediments of the Mahanadi varies from very fine skewed to coarse skewed. The monsoon sediments are more coarsely skewed than the pre-monsoon. The bed sediments with skewness values ranging from  $\phi = 0.04$  to  $1.70$ , indicate the presence of more finer material in the distribution.

Table IV.9

Statistical parameters of suspended sediments (units in  $\phi$ )

Sample no.	Mean	Variance	Std.Dev.	Skewness	Kurtosis
3	8.37	4.83	2.20	0.36	1.45
6	7.98	6.94	2.63	0.52	1.67
16	5.79	0.27	0.51	0.76	2.72
22	11.80	0.82	0.90	-0.76	2.90
25	11.50	0.90	0.95	-0.26	2.11
26	10.12	5.39	2.32	-1.02	2.77
31	11.59	0.88	0.93	-0.51	2.52
34	10.80	3.18	1.78	-0.31	1.75

Table IV.10  
 Statistical parameters of bed sediments ( units in  $\phi$ )

Sample no.	mean	Variance	Std.Dev.	Skewness	Kurtosis
2	0.58	0.86	0.93	0.36	2.09
3	0.86	1.57	1.25	0.35	1.97
4	1.04	0.95	0.97	0.19	2.98
6	0.79	1.04	1.02	0.06	1.89
7	0.28	0.94	0.97	1.17	3.87
8	0.31	0.75	0.87	0.98	4.08
9	0.61	0.59	0.77	0.48	4.27
10	0.43	0.53	0.72	0.09	2.25
11	0.08	1.03	1.01	2.44	9.53
12	2.56	0.30	0.55	1.44	5.13
13	1.41	0.57	0.75	0.15	4.65
14	1.16	1.90	1.38	0.05	1.71
15	2.52	0.13	0.36	1.09	5.96
16	2.44	0.16	0.40	1.70	7.23

#### IV.4.1.4 Kurtosis (KG)

It measures the ratio between the sorting in the "tails" of the distribution and the sorting in the central portion of the distribution. If the central portion is better sorted than the tails, the distribution is said to be excessively peaked or Leptokurtic. If the tails are better sorted than the central portion, the distribution is said to be flat peaked or Platykurtic. The suspended sediments in Mahanadi are very Leptokurtic and bed sediments are very Leptokurtic to extremely Leptokurtic.

#### IV.5.2 Mineralogy

Naidu et al. (1985), have reported the mineralogy of the  $<2$   $\mu\text{m}$  fraction of the bed load of the Mahanadi river. In the present work, a qualitative study on the mineralogy of the suspended and bed sediments (bulk) was done with a view to ascertain whether the theoretically predicted mineral assemblages agree with the actually identified clay minerals or not. Table IV.11 and Table IV.12 give the mineralogical composition of the suspended and bed sediments of Mahanadi. The semi-quantitative method (Biscaye, 1965; Carrol, 1970) was used to calculate the percentage of each mineral. The identification of minerals is given in Appendix. Table IV.13 and Table IV.14 give the percentage of clay minerals in suspended and bed sediments.

Table IV.11  
Mineralogy of suspended sediments ( in percent )

Sample no.	Quartz	Feldspar	Calcite	Dolomite	Chlorite	Kaolinite	Mont.	Illite
1	30	-	35	21	0.33	13	-	-
2	12	1	28	55	-	4	-	-
3	62	1	6	12	11.0	8	-	-
4	58	3	16	0.65	11.0	1	-	11
5	38	-	59	-	-	-	3	-
6	68	-	-	-	-	32	-	-
7	92	0.5	-	0.36	-	1.04	1.5	4.5
8	26	-	31	4.5	-	35.50	-	3
9	4.5	-	75.5	16.0	-	3.0	1.5	-
10	30.5	-	51.0	2.0	9	-	7.25	1
11	58.0	16	-	-	12	-	14.0	-
14	25.0	-	-	71.0	4	-	-	-
15	-	12	-	63.0	-	6	19.0	-
16	24.0	17	-	30.0	-	-	7.0	2



Table IV.12

Mineralogy of bed sediments (in percent)

Sample no.	Quartz	Feldspar	Amphibole	Calcite	Dolomite	Chlorite	Kaol.	Mont.	Illite
3	92	1	0.5	4.5	0.5	0.5	-	1	-
4	76	18	-	0.5	1	-	2	1.5	1
5	88	0.5	0.5	1.5	1.5	6.5	-	0.5	1
6	71	22.5	0.5	0.5	0.5	-	1.5	0.5	2.5
7	78	17	0.5	0.5	0.5	-	1.5	1.5	0.5
8	89	2.5	0.5	1.0	0.5	3	-	1.5	0.5
9	82	9.5	-	0.5	0.5	-	0.5	0.5	5
10	90	3	0.5	1.0	1	2	-	1	1.5
11	88	2.5	1.5	1.5	2	1.5	-	1	1.5
12	90	5	0.5	0.5	1	-	1	0.5	1.5
13	86	10	0.5	0.5	0.5	-	1	0.5	1
14	66	4	1.5	2.0	1.5	23	-	-	2
15	92	5	-	1.0	1.0	1	-	-	-
16	89	4	1.0	0.5	1.0	-	1.5	1.5	1.5

The suspended sediments are dominated by detritals (quartz and feldspar) and carbonates (calcite and dolomite). In all samples kaolinite occurs invariably with montmorillonite. Ramesh (1985), reported chlorite to be the dominant clay mineral in the suspended sediments of Krishna river and Jha (1986), found out illite to be the main clay mineral in the suspended sediments of Yamuna. Clay minerals are good indicators of the climate and soil genesis processes. Montmorillonite is formed mostly in areas with excellent drainage system. Chlorite and illite are inherited minerals, formed by the degradation of chlorite and mica of the source rock. Manickam et al. (1985), have shown for Loire river, France that kaolinite and illite show a positive correlation with discharge whereas chlorite and montmorillonite have a weak negative relationship with river discharge.

There is a considerable decrease of carbonates in the bed sediments. Quartz and Feldspar make up more than 80 % of the bed sediments. Montmorillonite and illite dominate in the clay mineral assemblages. Naidu et al. (1985), reported the presence of expandable clay minerals, illite and kaolinite in equal proportions for Mahanadi. This was attributed to the fact that the pre-dominance in the drainage basin of pre-cambrian granulites and charnockites, and weathering in a tropical humid climate. The bed loads of the Ganga and its tributaries are dominated by illite with smaller proportions of chlorite. The Narbada, Cauvery, Tapti, Krishna and Godavari bed loads have a greater pre-dominance of expandable clay minerals with relatively

Table IV.13  
 Percentage of clay minerals in suspended sediments

Sample no.	Kaol.	Chlorite	Mont.	Illite
1	97	3	-	-
2	100	-	-	-
3	70	30	-	-
4	3	32	-	65
5	-	-	100	-
6	100	-	-	-
7	10	-	4	86
8	85	-	-	15
9	80	-	20	-
10	-	61	25	14
11	-	63	37	-
14	-	100	-	-
15	39	-	61	-
16	-	-	46	54

Table IV.14

Percentage of clay minerals in bed sediments

Sample no.	Kaol.	Chlorite	Mont.	Illite
3	-	50	50	-
4	42	-	16	42
5	-	74	3	23
6	22	-	4	74
7	46	-	23	31
8	-	63	16	21
9	5	-	2	93
10	-	36	9	55
11	-	21	7	72
12	24	-	6	70
13	31	-	8	61
14	-	85	-	15
15	-	100	-	-
16	29	-	14	57

minor amounts of illite, kaolinite and chlorite (Naidu et al., 1985). Raymahasay (1987), has studied the clay minerals as tools for control of pollution. He observed that montmorillonite is capable of removing larger amounts of cationic pollutants compared to kaolinite.

## CONCLUSION

1. The Mahanadi river water is alkaline in nature. The EC changes with season indicating the variation of ion chemistry with season.  $\text{Cl}^-$ ,  $\text{HCO}_3^-$  and  $\text{SO}_4^{--}$  make up more than 70 % of the total ions. The chloride and bicarbonate concentration in Mahanadi is more than the other Indian rivers. Sulphate concentration is lower than the average for Indian rivers. Dissolved silica concentration is higher in the monsoon season. The source of Ca, mg appear to be the same. Most of Na, Ca is derived from rock weathering. The  $\text{Ca} + \text{Mg} / \text{Na} + \text{K}$  shows that the carbonate source rock influences the water chemistry in the Mahanadi.

2. Mineral assemblages expected to be in equilibrium with the chemical composition of Mahanadi river water are, dolomite in carbonate equilibria, kaolinite, illite-montmorillonite and chlorite in silicate system, irrespective of the seasonal variation. The theoretically predicted mineral assemblage confirm with the observed suspended sediment mineralogy.

3. More than 95 % of the water discharge is in the monsoon particularly in the month of Aug.- Sept. The dissolved transport dominates over physical transport, being almost four times. The erosion rate is controlled by the basin area and elevation, but there is little relationship between physical and chemical erosion rate. The rate of lowering of the drainage basin is 1.59 mm/yr. on the average. Mahanadi at Tirtol annually delivers 11.56 million tonnes of load to the Bay of Bengal.

4. The suspended sediment is mostly fine clay and bed sediments , medium sand in nature. The sediments are moderately sorted, fine to coarse skewed and Leptokurtic in nature.

5. Quartz, Feldspar and the carbonates are the major mineral species in the sediments. Kaolinite and Montmorillonite in suspended sediments. Montmorillonite and Illite dominate in clay minerals of bed sediments.

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## APPENDIX

### Water Analysis

#### pH and Electrical Conductivity (EC) :

pH and EC of water samples were measured by pH-Conductivity meter model CONSORT C425. The pH electrode is active and stable only after wetting. For this purpose, it must be immersed for at least ten hours in 0.1 M HCl or in a buffer of pH 4 to 7. During short interruptions the electrode should be immersed in KCl solution, diluted HCl or a buffer of pH 4 to 7. Before using, the reference part of the electrode is topped with a 3.5 M KCl solution. After rinsing the electrode with distilled water, it was immersed in a buffer solution of pH 6.87 (25 °C), the CAL knob was adjusted, then the SLOPE knob was adjusted after immersing the electrode in a buffer solution of pH 4.01 (25 °C). After the instrument is calibrated, pH of each water sample was determined. Three readings of each sample were recorded to get accurate result. The samples were stirred during measurement to promote homogeneity.

EC was measured in microsimens per centimetre ( $\mu$  /cm.). The instrument was first calibrated and set for 0.01M KCl standard (1287  $\mu$ S/cm. at 25 °C). Three readings of each sample was taken.

**Bicarbonate :** The bicarbonate was determined following the Potentiometric titration method. Standards of bicarbonates (ranging from 5 ppm to 300 ppm) were prepared. 25 ml of each standard and samples were titrated against 0.006 N HCl. The end

point of the reaction is attained when the solution comes to a pH of 4.5. A graph was plotted for standard concentration vs. volume consumed. Then the concentration of the samples were determined from the graph plotted.

**Chloride** : Chloride, in the form of chloride ion ( $\text{Cl}^-$ ) is one of the major inorganic anions in water. It was estimated by Mohr's titration method. Standard solutions of chloride of various concentrations were prepared. 25 ml. of each water and standard solutions were titrated against 0.06 N Silver nitrate solution. Potassium chromate was used as an indicator. The color change is from pink to yellow. Knowing the value of silver nitrate consumed by each sample, the concentration of chloride in each sample was ascertained from the graph of standard solution of chloride vs. volume of silver nitrate consumed.

**Fluoride** : Fluoride concentration was determined using pH/Ion meter- 135. 25 ml. of each solution is taken, equal volume of Total Ionic Strength Adjustment Buffer (TISAB : 1 molar sodium chloride + 0.25 molar acetic acid + 0.75 molar sodium acetate + 0.001 molar sodium citrate) is added, to equalise the ionic strength of the solution and also to suppress the interference of other ions, so that the electrode functions directly as a concentration probe. The instrument was calibrated for the standard fluoride before reading the concentration of the samples.

**Sulphate** : The sulphate concentration was determined by titration method after Fritz and Yamamura (1955) and Haartz et al. (1979). Before titration, the samples were passed through a cation- exchange resin to remove interfering cations and the titration was carried out in 80 % ethanol, to keep the barium sulphate in solution. In order to activate the resin, 30 % HCL is passed through the column. After that it was rinsed with 100 ml. distilled water. Then approximately 70 ml. of unacidified standard and sample was passed through the column. The first 40 ml. of the sample was discarded and the rest was collected for the analyses.

Sulphate standards of various concentrations were prepared by using sodium sulphate. 10 ml. of each standard and sample were taken, 40 ml. of ethanol was added to it. This was titrated against 0.005 M barium perchlorate in 80 % ethanol (prepared by taking 2 gm. barium perchlorate in 200 ml. deionised water and 800 ml. of ethanol) . Thorin was used as indicator. The color change at the end point being pink .

**Phosphate** : Phosphate was determined by the ascorbic acid method. Phosphate standards of concentrations ranging from 0.01 ppm to 0.1 ppm were prepared from  $\text{KH}_2\text{PO}_4$ . 40 ml. of each standard solution and sample is taken, 5 ml. of molybdate antimony solution and 2 ml. of ascorbic acid solution was added (strictly in that order). The mixture was diluted to 50 ml. and the optical density was measured at 650 nm. using CECIL SPECTROPHOTOMETER MODEL 594. Molybdate solution was prepared by dissolving antimony



tartarate in 400 ml. of 4N-  $H_2SO_4$  and making the total volume upto 500 ml. with the same acid. Ascorbic acid (0.1 M) was prepared by dissolving 2 gm. of ascorbic acid in 100 ml. of distilled water.

Sillica : The dissolved sillica concentration was determined by the molybdo-sillicate method. Standard solutions of different concentrations ranging from 0.1 ppm. to 5 ppm. were prepared by dissolving  $Na_2SiO_3$ . 20 ml. of each standard and water samples were taken, 10 ml. of ammonium molybdate solution and 15 ml. of reducing reagent was added. Ammonium molybdate solution was prepared by dissolving 2 gm. of ammonium molybdate in 10 ml. distilled water and 6 ml. conc. HCL and the total volume was made upto 100 ml. by diluting it with distilled water. Reducing reagent was prepared by mixing 100 ml. metol sulphite solution, 60 ml. of 100 % oxalic acid and 120 ml. of 25 % sulphuric acid and the total volume was made upto 300 ml. using distilled water. Metol sulphite solution was prepared by dissolving 5 gm. of metol in 210 ml. of distilled water and 3 gm. of sodium sulphite was added and the total volume was made upto 250 ml. using distilled water.

The samples were stirred and kept for 3 hours to complete the reaction. The optical density was measured for standard and water samples at 650 nm. using Cecil spectrophotometer.

Ca, Mg, Na, K : Ca, Mg were analysed in the absorption mode and Na, K were analysed in the emission mode by GBC 902, double beam ATOMIC ABSORPTION SPECTROPHOTOMETER using different concentrations of standards of corresponding elements. To avoid chemical interferences, suppressants were used.

### Identification of minerals from XRD chart :

Montmorillonite : It is identified by its 001 peak at 17 Å in the Mg-saturated and glycolated sample. Sometimes the broad nature of this peak is due to variations in expansion after glycolation and variations in crystallinity. Montmorillonite has its 001 peak at 12.4 Å in the k-saturated sample.

Illite : The main basal peak of the illite is at 10 Å with other peaks at 5 Å and 3.3 Å. The peaks remain unaffected upon glycolation and heat treatment.

Kaolinite and Chlorite : These two minerals give peaks almost at the same spacing and hence their identification becomes difficult. Biscaye (1964), pointed out that kaolinite in addition to two strong peaks at 7.16 Å and 3.58 Å, gives always a very small peak at 2.38 Å. Similarly, chlorite in addition to 7.05 Å and 3.54 Å peaks, shows a relatively smaller peak at 4.7 Å. Therefore, whenever the chlorite peak at 4.7 Å is present, the peak at 7 Å and 3.5 Å is considered as kaolinite peak.

Quartz : Quartz gives a strong peak at 3.34 Å and another smaller peak at 4.26 Å.

Alkali Feldspar : It shows a characteristic peak at 3.25 Å.

Plagioclase Feldspar : The peak at 3.20 Å is considered for the identification of plagioclase feldspar.

Calcite : shows a prominent peak at 3.04 Å.

Dolomite : The peak at 2.89 Å is identified as dolomite.

Amphibolite : shows peak at 2.82 Å.

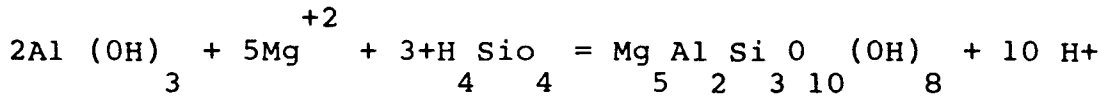
Calculation of moment measures

1 Class interval (mm)	2 D Mid point (mm)	3 W Weight (g)	4 D x W Product	5 D - M Mid-point deviation	6 <sup>2</sup> (D-M)	7 <sup>3</sup> (D-M)	8 <sup>4</sup> (D-M)	9 <sup>2</sup> W(D-M)	10 <sup>3</sup> W(D-M)	11 <sup>4</sup> W(D-M)
1-2	1.5	5.31	7.695	1.043	1.025	1.040	1.053	5.443	5.520	5.592
0.5-1	0.75	8.70	6.525	0.263	0.069	0.018	0.005	0.600	0.158	0.042
0.25-0.5	0.375	12.59	4.721	-0.112	0.013	-0.001	0.0002	0.164	-0.018	0.002
0.125-0.25	0.1875	9.13	1.712	-0.300	0.090	-0.027	0.008	0.822	-0.247	0.074
0.0625-0.125	0.031	2.49	0.077	-0.456	0.208	-0.095	0.043	0.518	-0.236	0.108
		44.25	21.57					8.481	4.808	5.963

Moment	Standard notation	Notation used in grain-size calculation	Calculation	Answer	Statistic
$m_1$	$x/n$	$(DxW) / W$	$= 21.57/44.25$	$= 0.487 \text{ mm}$	mean (M)
$m_2$	$(x-\bar{x}) / (n-1)$	$W (D-M) / W$	$= 8.481/44.25$	$= 0.192 \text{ mm}$	variance
		$m_2$	$0.192$	$= 0.438 \text{ mm}$	Standard Deviation
$m_3$	$(x-\bar{x}) / (n-1)$	$W (D-M) / W$	$= 4.808/44.25$	$= 0.109 \text{ mm}$	
		$m / m_2$	$= 0.109/0.084$	$= 1.298 \text{ mm}$	Skewness
$m_4$	$(x-\bar{x}) / (n-1)$	$W (D-M) / W$	$= 5.963/44.25$	$= 0.135 \text{ mm}$	
		$m / m_2$	$= 0.135/0.037$	$= 3.649 \text{ mm}$	Kurtosis

Phase diagram for MgO Al<sub>2</sub>O<sub>3</sub> - SiO<sub>2</sub> - H<sub>2</sub>O system

Gibbsite - chlorite :



Gibbsite

Chlorite

$$K = \frac{a_{\text{H}^+}}{a_{\text{Mg}}^5 a_{\text{H}_4\text{SiO}_4}^3} = \frac{1}{(a_{\text{Mg}})^5 \times a_{\text{H}_4\text{SiO}_4}^3}$$

$$a_{\text{Mg}}^5 a_{\text{H}_4\text{SiO}_4}^3 = \frac{1}{(a_{\text{H}^+})^{10}}$$

$$a_{\text{Mg}}^5 a_{\text{H}_4\text{SiO}_4}^3 = \frac{1}{(a_{\text{H}^+})^{10}}$$

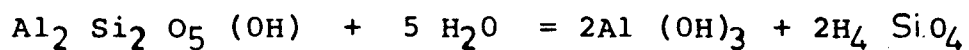
$$\text{or } K a_{\text{H}_4\text{SiO}_4}^3 = \frac{1}{(a_{\text{Mg}})^5 (a_{\text{H}^+})^{10}} \quad \text{--- (1)}$$

$$\begin{aligned} \Delta F_f &= \Delta F_p^\circ - \Delta F^\circ \\ &= -1961.70 + 5 \times 108.7 + 3 \times 312.6 + 2 \times 276.17 \\ &= 71.94 \text{ Kcal/mol} \\ &= -1.364 \text{ Log } K - 52.74 \\ K &= 10 \end{aligned}$$

$$\begin{aligned} \text{From eq. (1)} \quad \text{Log } K + 3 \text{ Log } a_{\text{H}_4\text{SiO}_4} + 5 \text{ log } a_{\text{Mg}}^2 - 10 \text{ Log } a_{\text{H}^+} &= 0 \\ \text{or} \quad \text{Log } (a_{\text{Mg}}^2) &= \frac{-3}{2} \text{ log } a_{\text{H}_4\text{SiO}_4} + 10.542 \\ &= \frac{-3}{5} \text{ log } (a_{\text{H}^+}) \end{aligned}$$

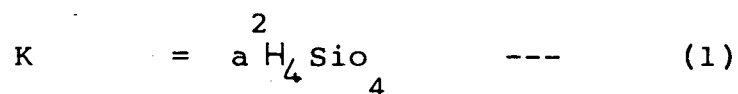
Plot a line using this equation

Kaolinite - Gibbsite :



Kaolinite

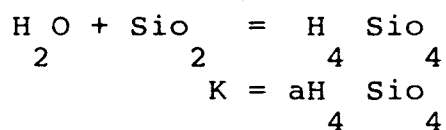
Gibbsite



$$\begin{aligned} \Delta F_f &= \Delta F_p^\circ - \Delta F_R^\circ \\ &= 2 \times (-276.17) + 2 \times (-312.6) - (905.6) + 5 \times 56.69 \\ &= 11.52 \text{ Kcal/mol} \\ &= -1.364 \log K \\ \log K &= -8.445 \end{aligned}$$

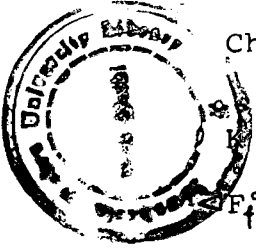
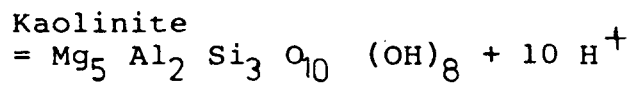
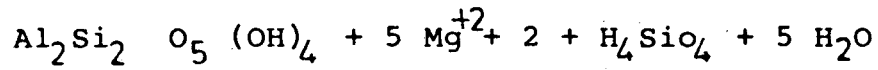
$$\begin{aligned} \text{From eq.(1)} \log K &= 2 \log a_{\text{H}_4\text{SiO}_4} \\ \text{or } \log a_{\text{H}_4\text{SiO}_4} &= -4.222 \end{aligned}$$

Amorphous Sillica :



$$\begin{aligned} \Delta F_f &= 3.67 \text{ Kcal/mol.} = -1.364 \log K \\ \log K &= -2.690 \end{aligned}$$

Chlorite - Kaolinite :



Chlorite

$$K = \frac{a^{10}\text{H}^+}{(a\text{H}_4\text{SiO}_4)^4 \times (a\text{Mg}^{+2})^5} \quad (1)$$

$$\Delta F^\circ = 83.46 \text{ K cal/mol.} = -1.364 \log K$$

From eq. (1)  $\log K + \log \frac{a\text{H}_4\text{SiO}_4}{(a\text{Mg}^{+2})^5} = -5 \log \frac{(a\text{Mg}^{+2})^2}{(a\text{H}^+)^2}$

or  $\log \frac{(a\text{Mg}^{+2})^2}{(a\text{H}^+)^2} = -1/5 \log \frac{a\text{H}_4\text{SiO}_4}{(a\text{Mg}^{+2})^5} + 12.23$

plot a line using this equation.

Calculation of Pco =

Use the equation  $\log P_{\text{CO}_2} = 7.9 + \log \frac{m\text{HCO}_3^-}{\text{pH}}$

(B.C. Raymahasay, 1986)